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SAN ANDREAS RIFT, CALIFORNIA

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ABSTRACT

This paper describes the San Andreas Rift or strike-slip shear of California. After a statement of the general relations of the rift, four sections are distinguished and one of them, the stretch of the rift in central California, is discussed in some detail with reference to (1) the fault type; (2) the stress problem; (3) the associated minor structures, such as thrusts and folds; (4) the antiquity of the rift; (5) deductions from schlieren and jointing in granites; and (6) the direction of the orogenic pressure to which the assemblage of structures may be attributed. The facts throughout are analyzed according to the principles governing mechanical rock deformation.

GENERAL ACCOUNT

DESCRIPTIVE

The San Andreas Rift or Shear is a parting in the earth's crust along the coast and in the Coast Ranges of California. It extends from Punta Arenas (lat. 39° N.) southeasterly to the Salton Basin (lat. 33° N., approximately). Its observed length exceeds 900 km. (550 miles), but neither end is defined. At the north it passes under the Pacific and presumably continues as a structural feature of the ocean bed. In the south it disappears under the sediments of the Salton Basin, but it may be assumed that the zone of shearing, which is the fault zone itself, persists into the Gulf of California.

The surface expression of the rift is a crushed zone that often exceeds a mile in width and may expand to as much as 8 km. (5 miles) or more. Where thus widened, the fault zone constitutes a node of intense fracturing, in which the effective local stresses may

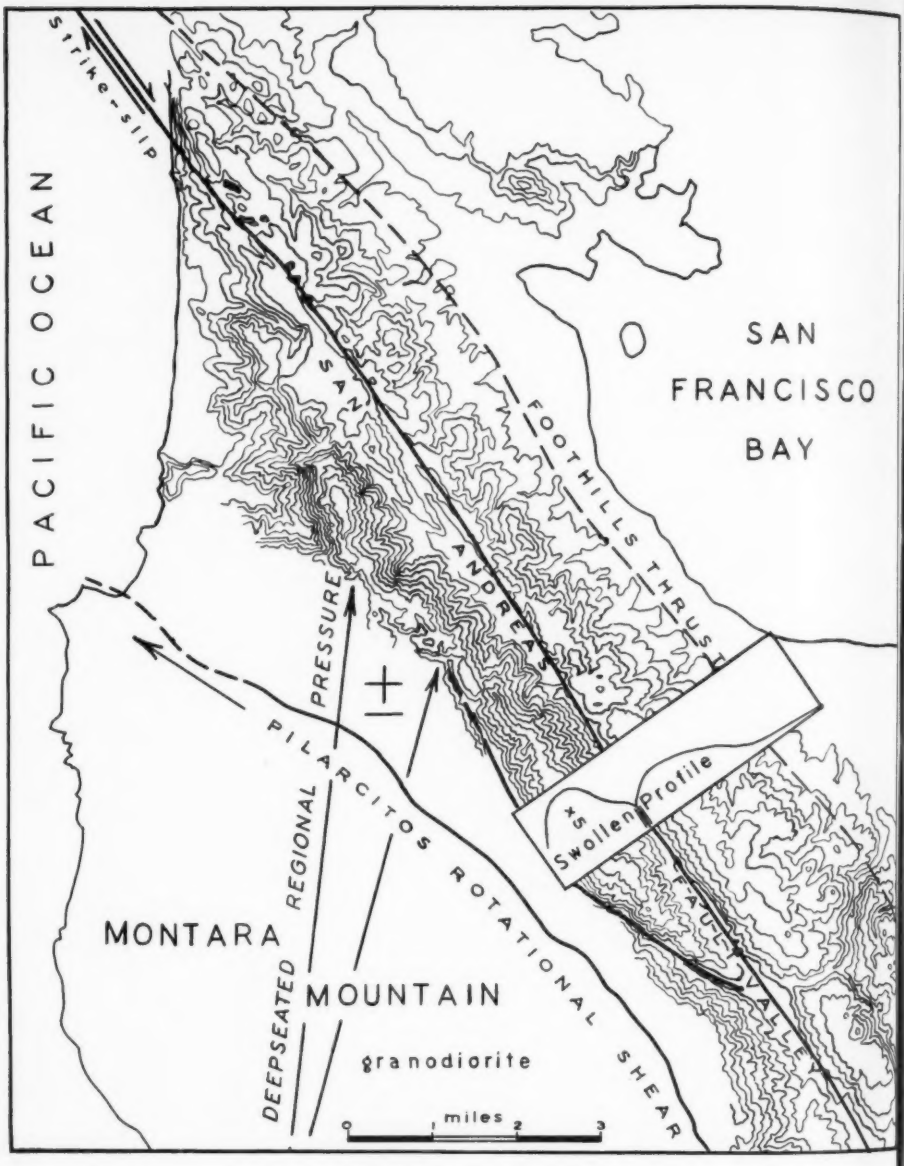

FIG. 1.—San Andreas strike-slip shear in the type locality

have been compressional and tensional and rotational. Blocks within such an area are completely isolated by minor faults. They are pushed about, mayhap up or down, mayhap over or under, perhaps lengthwise along the strike—in whatever way the local internal stresses of translation or rotation within the fault zone may have determined. Strips of adequate extent and covered by sediments may exhibit anticlinal and synclinal folds. Folding of similar character is developed outside the rift proper, and it may be noted that the axes of such folds have a definite angular, not parallel, relation to the strike of the great shear.

Below the superficial level of fracture the San Andreas Shear is a tight fissure or fissure system, according to the action that produces earthquakes. They are understood to result from elastic distortion of rocks, caused by frictional resistance to slipping on the fault. The fact that friction restrains the slip proves the tightness of the fissure. It has also become apparent that there is one major shearing plane or zone of closely spaced partings, which is practically straight for considerable distances on the strike and yet curves around mountain masses, where these offer relatively great resistance to direct displacement. The fault plane stands vertical or nearly so and presumably extends through the rigid outer skin of the lithosphere into the plastic substratum. Were this inference not correct, it would be necessary to make the improbable assumption that there exists a horizontal gliding surface in the outer crust.

Distributed along the rift are rocks of widely diverse ages and origins, ranging from Mesozoic sediments and granites to the Recent alluvial fans and representing practically every epoch of late Mesozoic and subsequent history. They are invariably sheared, crushed, or folded, according to their mechanical reaction to deformation. Their condition clearly demonstrates the intense and prolonged and repeated stresses to which they have been subjected. But out of the apparent chaos there emerge upon investigation definite structures, developed in accordance with mechanical principles that govern rock deformation. The study of the section in the vicinity of Cajon Pass, east of Los Angeles, as described by Noble[1] presents a typical

[1] L. F. Noble, "San Andreas Rift and Some Other Active Faults in the Desert Region of Southern California," *Seis. Soc. Amer. Bull.* 17 (1927), pp. 25–39.

picture of the effects of shearing and crushing, which are characteristic of the rift.

The great primary shear, the San Andreas Rift, is frequently paralleled by minor faults, which may be regarded as secondary to it. They diverge from it to a distance of several kilometers; then they adopt a parallel strike and extend for some tens of kilometers in parallel to where they converge upon and rejoin the major fault. The region of the junctions is one of complex and confused crushing. The strip between the two faults is commonly elevated; it may constitute a conspicuous ridge or mountain. The summit carries an earlier erosion surface, a portion of the Pliocene matureland or peneplain, which in turn supports residual heights. And this topographic surface may present flats or level crests along its length, and in transverse section may be arched so as to simulate an anticline superficially, though quite unlike one internally.[2]

The dip of the secondary fault is vertical or very steep, but where observable has been found inclined toward the major shear. Since the secondary joins the primary at both ends, it presumably does so along their extent, on the strike, but at considerable depth. Where that is the case, the intervening block is a wedge, and its elevation and deformation are effects of wedge-block faulting. The secondary thus differs from the primary in being a dip-slip fault, an upthrust (Fig. 3, p. 802).

One would infer that wedge-shaped mountains might be displaced horizontally, sternward (the wedge-point representing the bow) as well as vertically. Confirmation of this inference is found in the displacements of primary triangulation stations, demonstrated by the United States Coast and Geodetic Survey.[3] Mounts Tamalpais and Loma Prieta, which have been reoccupied as primary stations at intervals since 1857, have been shown to have moved in the direction which they would take if they yielded as wedges under pressure. The apparent shift of Mount Tamalpais, $2\frac{1}{2}$ feet, may be due to errors of observation, though it probably is real; that of Loma

[2] Robin Willis, "Physiography of California Coast Ranges," *Bull. Geol. Soc. Amer.*, Vol. XXXVI (1925), pp. 641–78.

[3] W. Bowie, "Comparison of Old and New Triangulation in California," *U.S. Coast and Geodetic Surv. Spec. Pub. 151* (1928), Map, p. 45.

Prieta, 5.5 feet is without question actual. In each of these cases the mountain block is a wedge cut out between the San Andreas Shear and a secondary fault; each has moved away from the point of the wedge, if at all; and each has been pushed up beyond other heights in the vicinity, and for that reason was chosen as a primary triangulation point, without any suspicion of its instability. Other stations in this vicinity which show similar displacements (Mocho, Mount Hamilton, Santa Ana, and Hepsedam) all lie on the far side of the Santa Clara Valley trough from Loma Prieta, in the distinct geologic province of Franciscan (Jurassic) rocks and in a separate mountain range, of extremely complex, faulted structures. Thrust faults and other evidences of great compression are of general occurrence there. The approximate uniformity of displacements, while suggesting a movement of the whole area as a unit, is more likely coincidence of degree of movement among blocks subject to about the same amount of squeeze.

The secondary faults of the above-described character resemble in mechanical effect the fracture that defines a chip or spall, struck off or pressed off of a block. They might be described as *spall* faults.

Intimately related to the secondary or spall faults are those of tertiary magnitude, which branch from the spall faults and dip toward them. They cut out a wedge, which is pushed up between them. Both fractures thus become upthrusts. The San Bruno fault in the San Francisco Peninsula[4] is one of these tertiary faults, and San Bruno Mountain is the upthrust block. It carries a level summit, a remnant of a peneplain, the level position of which indicates vertical uplift, without tilting.

One condition which may give rise to tertiary faults is shown in Figure 2. In consequence of the upward curvature of the secondary, rising from an initial attitude of 45° to verticality at the surface, the corner of the wedge is exposed to excessive pressure and pressed off.

The preceding analysis of minor faulting connected with the great shear of the San Andreas Rift enumerates only the more easily recognizable effects of pressure in relatively homogeneous, elastic rocks. Even in them the fracturing extends to the *n*th degree of

[4] A. C. Lawson, "Sketch of the Geology of San Francisco Peninsula," *U.S. Geol. Surv. 15th Ann. Rept.* (1895), pp. 399–476.

shearing and crushing, even to a stage where locally the angular blocks are reduced to rounded boulders and become embedded in clastic sand.

The mechanical effects are not limited to the narrow zone of the rift itself, even where it widens to several kilometers. The effects of compression extend to the entire width of the Coast Ranges and are of orogenic magnitude and intensity.

The direction of actual movement on the San Andreas Rift was demonstrated on April 18, 1906. Throughout central California, the mass southwest of the rift then jumped past the mass northeast of it, toward the northwest. As observed at the surface the horizontal shift averaged about 4 meters (13 ft.) through a distance of 435 km. (270 miles) along the strike. The maximum shift occurred near Stanford University, some 40 km. (25 miles) southwest of San Francisco, and it there amounted to 6.3 meters (21 ft.). The time required for the movement was but a few seconds, and the work done was estimated as equal to 13×10^{16} foot-pounds (1.8×10^{16} m.kg.).[5]

The relatively local and instantaneous displacement on the San Andreas Rift in central California is the latest manifestation of the movements which appear to have characterized it throughout Pleistocene and probably also during its earlier history since some indeterminate beginning. Streams which cross the rift zone are offset in the same sense as in 1906. In general, horizontal shifts that are recognizable in topographic features show the same effect. The total horizontal displacement of the southwest mass northwestward past the northeast body appears to be very notable, though not definitely determinable. On the other hand, there is abundant evidence of deep fault troughs, now filled with Mesozoic or Tertiary sediments, which in turn are proof of once elevated blocks. These are witnesses that testify to marked vertical changes of level, both upward and downward, and they are sometimes so related to the rift as to indicate that it was the mechanical factor in the displacements.[6]

[5] "California Earthquake of April 18, 1906; Report of State Earthquake Commission, Vol. II: 'Mechanics of the Earthquake'" (by H. F. Reid), *Carnegie Inst. Wash. Pub. 87* (1910), pp. 15 ff.

[6] J. P. Buwalda, "Certain Inferences Regarding the Nature of the Movements along the Haywards Fault Zone, California," *Bull. Geol. Soc. Amer.*, Vol. XXXVII (1926),

The evidence of vertical movements appears to be most pronounced in the great masses of Jurassic and Cretaceous sediments, which filled so-called "geosynclines" and now constitute mountains; but the remarkable thicknesses of Pliocene and Pleistocene formations are scarcely less impressive. The horizontal shifts are most clearly demonstrable in physiographic and structural relations that have developed during the late Tertiary and subsequently; it would, however, be hazardous to deny on negative evidence alone that they had not been a feature of the faulting in older times. Displacements in the two senses, horizontal and vertical, are mechanically related and reciprocally consistent, each with the simultaneous occurrence of the other. Both have presumably been characteristic of the San Andreas Rift throughout its history, though undoubtedly one or the other has been more pronounced here or there and from time to time.

WHAT FAULT TYPE?

Had the San Andreas been classified before 1906, it would probably have been described as a "normal fault," meaning a gravity, dip-slip fault. The rectilinear trace and vertical attitude would have sufficed to put it in that class, in the then state of knowledge of faulting. But observation of the dominant horizontal shift at once took it out of the class of faults attributable to gravity. It could not be regarded as a dip-slip fault, since it was clearly a strike-slip. As such it was recognized as an effect of a shearing stress, which must be appropriately oriented to produce a vertical shear.

Branner, Gilbert, Lawson, and Reid, to mention only the more prominent among the geologists who studied the earthquake, all appreciated the special character of the shift. Of their accounts, Gilbert's is the simplest statement.[7]

> The plane of the earthquake-causing fault, where it appears at the surface, is approximately vertical. The movement which took place along this fault is

p. 212; B. L. Clark, "Studies in the Tectonics of the Coast Ranges of California," *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), p. 163; "Tectonics of the Valle Grande of California," *Amer. Assoc. Petrol. Geol. Bull. 13* (1929), pp. 199–238; R. D. Reed, *Geology of California* (Tulsa: Amer. Assoc. Petrol. Geol., 1933).

[7] G. K. Gilbert, "The Earthquake as a Natural Phenomenon," *U.S. Geol. Surv. Bull. 324* (1907), pp. 1–13.

approximately horizontal. As the statement of these relations is sometimes found confusing, they are here illustrated diagrammatically.

The diagram [below] represents a rectangular block as if cut from the land. ..... The dotted line *SS'* indicates the surface outcrop of the old fault, trending northwest and southeast, this plane cutting the block on the line *SD*. *AB* stands for any straight line on the surface of the land—such as would be defined by a road, a fence, a row of trees, crossing the fault at right angles. The lower diagram represents the same rectangular block after the earthquake, its two parts dislocated by sliding horizontally along the fault plane, and the line *AB* made discontinuous by an offset.

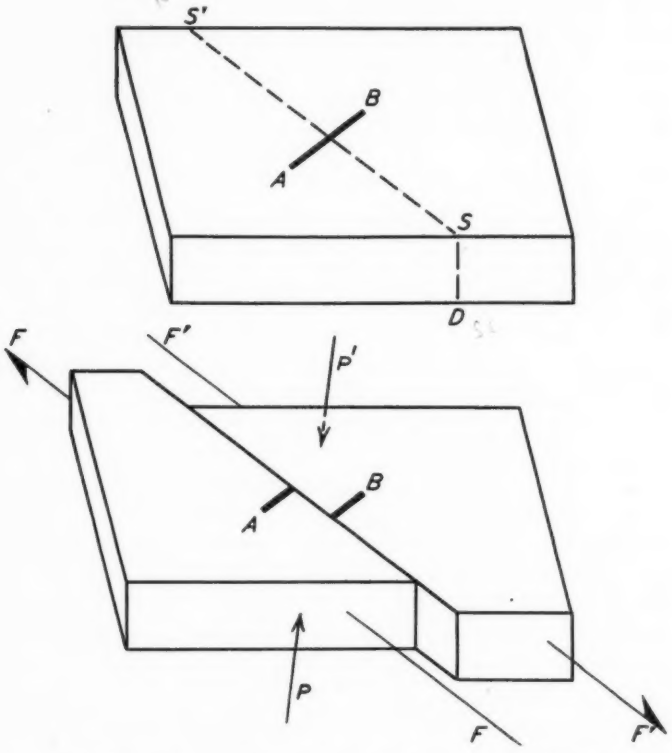

FIG. 2.—"Diagrams illustrating the nature of the earthquake-making fault" (Gilbert); a strike-slip shear.

It is obvious that the plane $SS'D$, thus described by Gilbert, is a mechanical shear. As such it is attributable to a force couple, such as $FF,F'F'$, indicated by the arrows which are here added to Gilbert's diagram. Recognition of the stresses FF and $F'F'$ does not, however, explain their origin; some further, adequate cause is demanded.

STRESS PROBLEM

According to mechanical principles, a force couple, such as is deduced above, may result from (1) simple translation of two bodies in opposite directions, parallel, but not directly opposed to each other; or (2) simple rotation of one body past another; or (3) combined translation and rotation, in consequence of the development of pressure, i.e., a stress, in a definite direction and to such an intensity as to cause shearing in the compressed mass. Any sliding which continued pressure in the same direction may occasion is then the effect of components that constitute a force couple, as FF, $F'F'$ in Figure 2. The stress also develops other components, which produce compression; and the association of sliding and compression is, in itself, proof of the action of the pressure.

In movements of simple, parallel translation, as in (1), there is no compression of the one moving part upon another; any slide moving between guides in a machine illustrates the conditions. The case is not common, if indeed possible, in geologic displacements.

The second condition of the development of a force couple is that one body shall rotate past another; as when an axle turns in a bearing. We can then conceive a case in which the perfect fit of axle and bearing results in rotary translation of the bodies past one another, without compression; but any misfit must produce the action of a cam, which is followed by compression and tension along adjacent sections of the moving bodies. This is one condition and a not uncommon one for the widening and narrowing of fissures and of veins that fill them. It may occur on a larger scale, but the development is limited by the weakness of rocks, which will not support more than a limited vacancy.

The third condition assumes a directed pressure, which produces shearing and is resolved into components parallel to and at right angles to the planes of shear. There are always at least two sets of

shearing planes, but it commonly happens in nature that one set, the one which meets with least resistance to slipping, develops more strongly than the other. The components parallel to that shearing plane then constitute a force couple which is the one that will cause displacement along the strike, strike-slipping, provided the original pressure was directed in a horizontal plane. Whereas the compo-

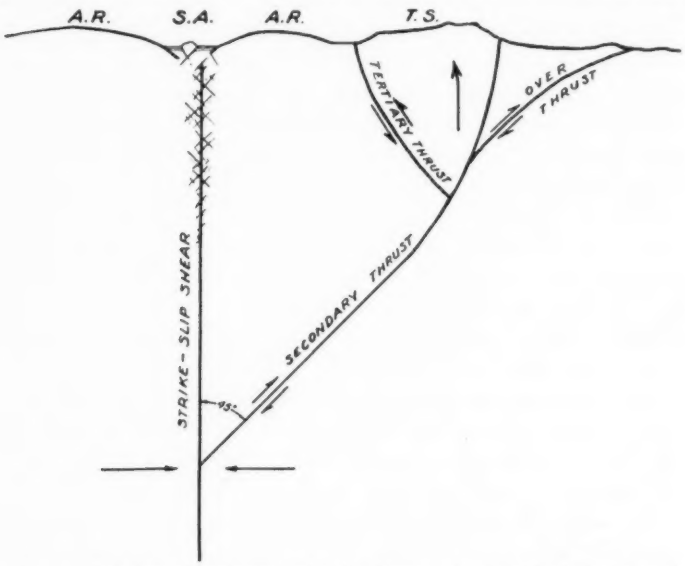

FIG. 3.—Relations of a primary, strike-slip shear to minor, dip-slip faults, when the pressure which causes the primary is resolved into components parallel and normal to the plane of the primary.

nents that are directed in a position normal to the shearing plane produce compression. The phenomena of secondary shears, thrusts, and folds, which are very generally associated with the San Andreas Rift, as also with other strike-slip faults, are results clearly attributable to such compression. Thus we have in the mechanical effects of horizontal shifts and the effects of compression the evidence that the San Andreas is due to a directed pressure, which according to mechanics must have acted upon the crust at an angle that approximated 45° to the strike of the shear.

Since the strike of the San Andreas is about northwest-southeast, the effective stress should impinge upon the fault plane from south or north, approximately. But whether from south or north remains a question. And back of that lies the problem of the cause. The pressure has been and is of orogenic magnitude. It has raised and is raising mountains. Thus the inquiry reaches to the broader phenomenon of the mountain growth in general.

We first take up the specific evidence of structures along the San Andreas Rift in central California.

SAN ANDREAS RIFT IN CENTRAL CALIFORNIA

The San Andreas Rift may be divided into four sections: (1) a northern stretch, extending from San Francisco Bay northwestward to Punta Arenas; (2) a central portion, which reaches from San Francisco Bay southeastward to where the fault turns easterly around the mass of San Emigdio Mountain; (3) an east-west reach, extending eastward from San Emigdio to the junction with the Garlock fault; and (4) the southern part that pitches into the Salton Basin (Fig. 7).

The northern section has not been closely studied and is not here described. The central portion is the subject of the immediately following description; and the southern part will be taken up in sequence.

The central section of the San Andreas Rift, between San Emigdio Mountain and San Francisco Bay, stretching from latitude 35° to latitude 38° N., is 400 km. (250 miles) long and strikes with but little variation N. 42° W. (Fig. 7). The straightness is remarkable and indicates an unusual uniformity of resistances from point to point as well as a definite alignment of stresses. A change of direction or intensity of stress or of orientation or weakness in the resisting mass introduces curvature in a shear. The line has been described as the boundary between two geologic provinces, which at the surface are characterized by totally unlike formations of pre-Cretaceous age. The one that lies southwest of the rift is underlain by granite and has been named "Salinia," from the Salinas Valley, with which it corresponds geographically. The area northeast of the rift is occupied largely by the Franciscan (Jurassic), a complex of sediments,

intrusives, and volcanics, both of the latter being of basic composition. A few slivers of granite stick up in it on fault contacts, as though thrust up from a granitic basement. These general relations suggest that the rift zone was already defined, either as a flexure, a dip-slip upthrust, or a strike-slip shear, during the Franciscan period. It seems probable that the region southwest of it was rising, that northeast of it was subsiding, and the vertical displacements were considerable. Strike-slip, horizontal movements may or may not have been commensurate. That was in Jurassic and later Mesozoic time.[8]

A peculiar feature of the San Andreas Rift in central California is the branching which occurs in the heart of the Coast Ranges and valleys east of Monterey Bay, in latitude 36°40′ N. The main rift suffers no change of course, but maintains its general strike of N. 46° W.; but a shear of similar magnitude splits toward N. 30° W. and develops as the Hayward strike-slip fault. The latter branches in turn, giving off the Calaveras strike-slip fault toward the right. The two pursue slightly divergent courses in a north by west direction to San Francisco Bay, a distance of 200 km. (120 miles). Both branches exhibit horizontal displacements of the southwest block in an anti-clockwise direction, as does the San Andreas itself. The effect is that which would be produced by movement of that block past a resisting body, which curved away toward the north from the point where the branching begins and thus left the rotational stress relatively free to spread into weaker terrane.

These branching, strike-slip shears resemble, though on a relatively enormous scale, the branching of mineral veins, such as occurs where a shearing stress has met with a change of direction or of intensity of the resistance; continuing, as though tangent to a curve, the shear splits into several divergent ones, each of which exhibits displacements similar to those of the parent shear. As the blocks or wedges move forward, they enter a widening space and the fissures relax in a manner favorable for intrusion of ore solutions or, perchance, of lavas.

A branch of the San Andreas, which is known as the Pilarcitos

[8] R. D. Reed and J. S. Hollister, *Structural Evolution of Southern California* (Tulsa: Amer. Assoc. Petrol. Geol., 1936).

fault, diverges from the rift zone on the southwestern side near latitude 37°20′ N., southwest of San Francisco Bay, and, after running parallel with it for about 30 km. (20 miles), bends more strongly westward to the coast. In its parallel course it is separated from the main shear by a strip that is not more than 3 km. (2 miles) wide, yet forms a high arched ridge (Cahill Ridge). The parallelism and the uparching are characteristics of the features produced by a secondary spall fault, and this part of Pilarcitos may be so classified. Where it bends westward the fault follows the outline of the Montara granite (quartz diorite) stock. Along the boundary the fault has the character of a rotational shear along the contact between the rigid batholith and a mass of relatively weak Franciscan sediments. Minor structures developed by the rotational shear are very complex and exhibit the action of a cam. Mylonite zones, thrusts, and close folding demonstrate the action of compression and dragging, which in part affect Eocene strata that were deposited unconformably on the granite. The structure of the Franciscan, adjoining on the northeast of the fault, is poorly exposed, but certainly extremely and complexly squeezed.

The Pilarcitos and San Andreas faults embraced between them an acute angle, which opens northwestward, in the direction of movement on the southwest side of the rift, where it lies. The effect of displacements has been, therefore, not only to compress the wedge but at the same time to force it out toward the wider section. Compression has consequently been relaxed or perhaps replaced by tension in the interior of it and most effectively so in the outermost part. This would appear to be one reason why the wedge has been intruded by diabase, and also why the larger bodies of the eruptive occur in the wider section.[9] The deformation affects Eocene strata and is therefore in part at least post-Eocene, while the intrusives are assigned to the Miocene.[10] It is thus probable that the orogenic

[9] Lawson, "San Francisco Folio: Geologic Map of San Mateo Quadrangle," *Geologic Atlas of United States No. 193* (Washington, D.C.: U.S. Geol. Surv., 1914); see also p. 11.

[10] H. L. Haehl and R. Arnold, "Miocene Diabase of the Santa Cruz Mountains, San Mateo County, California," *Amer. Phil. Soc. Proc.*, Vol. XLIII, No. 175 (1904), p. 16.

stress may have been active during the episode of eruption of the diabase.

Through the notice of Dr. L. Kober,[11] the Pilarcitos fault has achieved an undeserved importance in geologic circles. He describes it as a *Deckengrenze*, that is, the boundary of a decke or overthrust sheet, the basic idea being that the Montara batholith and the adjacent mass of Franciscan constitute two distinct overthrust sheets of old rocks, which supposedly lie upon younger ones. The misinterpretation is an item in the bold comparison of the American Cordillera, in its extent from Alaska to California, with the Alps. It is an example of the limitations of Swiss geology in matters relating to structure, which prevent its disciples from seeing anything except the hypothetical Alpine structure in any mountain range that is characterized by shears and thrusts. Similar effects of deformation are to be found, no doubt, generally in severely compressed zones of the earth's crust, since mechanical principles hold the world over; and it is not improbable that, some day, a rational interpretation of Alpine structure may be developed in accordance with those very principles.

TYPE LOCALITY

The San Andreas Valley, in the Coast Ranges southwest of San Francisco, is the type locality of the San Andreas Rift (Fig. 1). It is not particularly typical, since the ensemble of features is not duplicated elsewhere and the presence of a great fault might well not be suspected, unless determined by specific studies or revealed by an earthquake. It was the latter occurrence in 1906 that called attention to the valley as a fault valley and fixed the name.

In that it is not obviously due to faulting, nor even plainly due to erosion, the San Andreas is a peculiar valley. It is straight, like an Appalachian strike valley on soft strata, but there are no guiding strata. At the southeastern end it is blocked by bulky Black Mountain, across which the rift maintains its undeviating course. At its northwestern end the valley is closed by elevated blocks of marine Pliocene, jostled up in a broad fault zone. The outlet is situated on the northeastern side, about midway of the length, where San Mateo Creek has cut a little canyon across the ridge and so made its way

[11] L. Kober, *Die Gestaltungsgeschichte der Erde* (Berlin, 1925), p. 139.

out to San Francisco Bay. The length of the valley is but 30 km. (20 miles).

In minor topographic features the floor of the San Andreas Valley presents the complexity of the underlying structure. There are little hills and depressions without outlets; and also stronger ridges, due to raised slivers. There is no deep trough, although fresh-water gravels have accumulated locally to considerable thickness.

On either side, along the northeastern and southwestern margins of the faulted strip, stand relatively high ridges, their crests about 2 km. (1 mile) apart. They consist of soft rocks, chiefly sandstone and shale, yet are not eroded back in proportion to the width of the valley floor. Their profiles are markedly convex, suggesting bulging. Examination shows that the rocks are intensely sheared or crushed. They are reduced to small fragments and forced into one another to an extent that renders recognition of formations as structural elements impossible. This is the condition of the entire mass of the two ridges, especially where they consist of Tertiary strata. The stronger Franciscan and igneous rocks here and there appear as larger bodies, but they also are faulted.

The profiles of the marginal ridges thus fail to express the fault by abrupt scarps, such as might be expected and sometimes occur along the rift. Instead the smooth, but convex slopes exhibit the form of an arched peneplain, which can be seen rising from the floor to the summits of the ridges and over them down the farther slopes. Thus the physiographic profile of the ridges on either hand of the rift declares the effects of compression at right angles to the great shear.

FOLDING

The term "folding," which once expressed a simple effect of anticlinal and synclinal development in strata, is now used in various senses, and it becomes necessary to define one's meaning in employing it. The mechanics of folding require not only bending but also shearing on bedding planes; and this kind of deformation is possible only where there are bedding planes, on which shearing or slipping can take place. Thus, strictly speaking, folding can occur only in bedded formations. It is aside from the definition to consider how the bedding originates, whether by stratification, or as lava flows, or

by shearing in granite in response to stresses in overlying controlling strata, in the process of bending. But bedding of some sort is an essential condition of the evolution of folds, of anticlines and synclines, according to mechanical principles.

There is a looser usage, which employs the term "fold" to describe any arching whatever, whether in massive, unstratified rocks, or as a flexure of the surface of the earth, or as a broad swell of the crust. When linked with the idea of geanticlines or geosynclines, it is applied to any change of level, even, of whatever dimension, mechanics, or origin.

The looser usage is undesirable, because ill-defined. In that broad sense the structure may be an effect of shearing, or warping, or intrusion, or epeirogenic movement; and so through a multiplicity of meanings becomes meaningless. It is here used only in the strict sense, restricted to that mechanical effect which involves shearing on the bedding planes and bending, but which excludes arching by internal crushing or warping by any other method whatever. In this sense massive rocks, granite or basement complex, cannot be said to fold; they offer such resistance to bending that they shear more easily into angular blocks, and deformation proceeds by displacement of the rhombohedral fragments.

The arched ridges, which have been described as ranged along the sides of San Andreas Valley, are not anticlines in the restricted sense. Nor are the uplifted blocks, which are defined by secondary and tertiary faults, even though, as happens, they may consist of an internal core of older, flanked by younger, rocks. Yet it is true that all these forms occur with their longer axes oriented parallel to the strike of the major shears and at right angles to the direction of the compressive stress. They are thus placed in the position that would be assumed by true anticlines, such as would develop in sedimentary formations, free to fold.

The cases where sediments have been free to fold appear to have been relatively rare in the Coast Ranges. Either they have been folded during a pre-Tertiary episode to that degree that shearing later replaced folding, or they have been controlled by the distortion of the basement rocks and have yielded in response to local rather than regional stresses. The former condition is perhaps locally char-

acteristic of the Franciscan formation and to some degree of the Cretaceous. The latter is typical of the Tertiary and Pleistocene strata.

The distortion of blocks of the basement rocks is that which is best illustrated by pushing any rectangle into the form of a rhomb. It is well known as an effect of rotational strain and may be demonstrated by the device of the strain ellipsoid. Rectangular blocking-out follows from the action of a shearing stress. Deformation of the rectangular block results in shortening one diagonal and elongating the other.[12] When such a block of the crust consists chiefly of sediments or is deeply mantled by them, true anticlinal folding develops in the strata with the axes aligned normal to, at right angles to, the shortened diagonal (Fig. 4). They are thus oriented at an acute angle to the primary shear, not parallel to it. This is a prevailing relation of the axes of folds to the primary shears of the Coast Ranges.[13] It is observed in the little anticlines which constitute productive structures of the Los Angeles oilfields and elsewhere; it is characteristic of the folds in Tertiary strata, even of so large a one as the Coalinga anticline; and it also appears in the Franciscan formations where Weaver[14] has mapped them north of San Francisco.

A somewhat different interpretation is placed upon the relation of folds to faults by some geologists, and very different conclusions are reached regarding the relative ages of faulting and folding. Where the axes of folds extend to the primary shears, the fact that they end at the shear may be regarded as proof that the fold is the older structure and that it is cut off by the younger fault. The alternative view which links the two phases of deformation according to mechanical principles is disregarded where this opinion is espoused.[15] The test of the question may be sought by looking for the continuation of any fold beyond the fault that appears to have dis-

[12] B. Willis and Robin Willis, *Geologic Structures* (3d ed.; New York and London: McGraw-Hill Book Co., 1934), pp. 109, 133–35; M. K. Hubbert, "Direction of Stresses Producing Given Geologic Strains," *Jour. Geol.*, Vol. XXXVI (1928), pp. 75–84.

[13] Clark, "Tectonics of the Valle Grande and Surrounding Areas," *op. cit.*, pp. 199–238; maps, pp. 216, 232; R. N. Ferguson and C. G. Willis, "Dynamics of Oil Field Structure in Southern California," *Amer. Assoc. Petrol. Geol. Bull. 8* (1924), pp. 576–83.

[14] Chas. E. Weaver, personal communication, 1938.

[15] Reed, *op. cit.*, pp. 11–12.

placed it. We have but to refer to Gilbert's diagram (Fig. 2), where the line *A–B* may be taken as representing a fold. The studies on districts traversed by the San Andreas Rift are quite sufficiently complete to have demonstrated many such offsets, if they existed. Indeed they have been looked for assiduously in the effort to determine the amount of offset or shift on the rift. But they have not

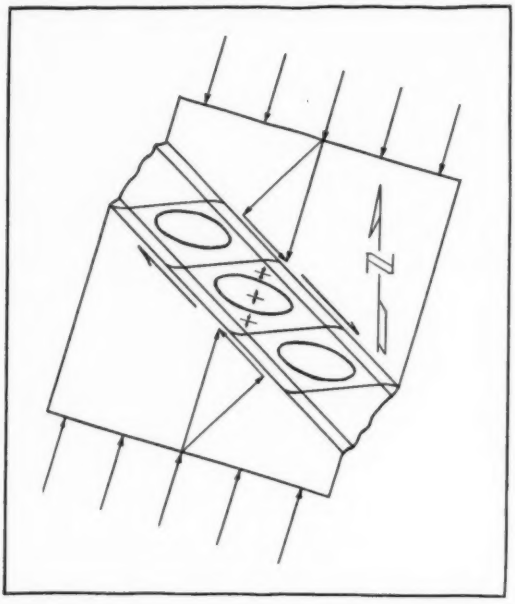

FIG. 4.—Relation of folds to primary, strike-slip shears, illustrated by the strain ellipsoid. (After Hubbert.)

been found. As the case now stands, we are confronted by the general fact that folds are so related to the primary faults as to prove that they both are effects of a common rotational stress.

ANTIQUITY OF THE RIFT

The relations of the rift to young topographic features and to post-Tertiary formations suffice to show that it has been active since pre-Pleistocene time. The former existence of raised blocks, that

were worn down, and of fault troughs, that have been filled with sediments, is evidence of orogenic displacements throughout Tertiary time in the long mountain zone traversed by the rift, and that that action may probably have been effective in producing displacements on the rift itself may reasonably be supposed. The general relations which have been described and which clearly indicate that the various faults, folds, and minor features may be interpreted as effects of one and the same system of contemporaneous stresses, repeatedly active and repeatedly inactive since Mesozoic time, confirm the impression that the rift is an ancient structural feature. Some details tend to support that inference. There is, for instance, the case of the occurrence of granite boulders in fossiliferous Eocene strata in the very strike-slip zone of the rift itself. It clearly shows that the granite was exposed on the fault line in that immediate vicinity in Eocene time.[16]

The locality lies in or on the northeastern margin of the granitic landmass, Salinia,[17] and may or may not have been covered by pre-Eocene sediments. But the exposure in any case indicates uplift, and its intimate place-relation with the rift presents a definite suggestion that the uplift was due to pre-Eocene faulting on the San Andreas shear.

In a detailed discussion of the evidence of greater or less antiquity of individual faults of the several systems observed in the Coast Ranges, Clark[18] presents evidence which leads him to the conclusion that a large proportion of the known primary faults are pre-Pliocene and presumably pre-Cretaceous in age.

Reed expresses a conservative view of the question as follows:

> Among the geologists most familiar with different parts of the long course of the fault, the notions held about its nature and history are very diverse. To some it is an ancient feature which has dominated the geologic events along its course and even throughout much of the Coast Ranges since the Jurassic at least. To others it is a recent feature, perhaps developed out of individual faults which were older, but only welded together in Pliocene time or later. At present there is little more reason for holding one of these views than the other.[19]

[16] Willis and Willis, *op. cit.*, p. 125, Fig. 54. [17] See p. 803.

[18] "Tectonics of the Coast Ranges of Middle California," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930), pp. 770ff.

[19] *Op. cit.*, p. 38.

Later Reed suggests on the ground of inferences concerning Lower Mesozoic geography of California that "the northern part of the course of the San Andreas fault was marked out, though not necessarily followed by a fracture, before the late Jurassic."[20]

STRUCTURES IN GRANITES

One of the older, though not the oldest, rock (it intrudes metamorphics) exposed along the San Andreas Rift in central California is the Coast Range granite. It may or may not be older than the Franciscan (Jurassic), but is pre–Upper Cretaceous. In considering the rift with reference to the possibility that it may be as old, it appeared that the internal structure of the granite and the mechanical effects of jointing might yield information regarding the direction of stresses during and shortly after the emplacement of the intrusive. If they were such as would produce the strike-slip shear in that orientation which it now has, in accordance with mechanical principles, then the case for antiquity would be strengthened.

Studies of flow structures and jointing in the granite have been made and are detailed in the immediate sequel, but it may here be stated in advance of the presentation of the facts that they definitely lead to the conclusion that the oldest recognizable stresses were directed in a north-south orientation.

Two masses of granite are exposed in northern central California in such relations to the San Andreas Rift as to serve the purpose of stress analysis. One of them will be designated by the name of the quarry in which the granite is exposed, the Logan quarry. The other constitutes Montara Mountain, which is well known through the work of Lawson (1895).

Logan quarry is situated on an isolated block of granite which constitutes the western wall of the San Andreas Rift 120 km. (75 miles) southeast of San Francisco in the Santa Cruz Mountains of the Coast Range. It is 35 km. (23 miles) east by south from Santa Cruz, on the Pajaro River. The rock is specifically a holocrystalline granodiorite, with faintly developed gneissic structure. It is exposed in a face about 30 m. (100 ft.) high and also on top by stripping. Its relation to any larger mass of intrusive is indeterminate, as is its

[20] Reed and Hollister, *op. cit.*, p. 84.

size, since the exposed boundaries are faulted, and it is largely covered by Pliocene marine sediments, which lie in a horizontal attitude upon it.

In 1924, when I first examined the structure of the granodiorite of Logan quarry, the methods of analysis which we owe to Hans Cloos had not come effectively to my attention, and my observations were limited to the problem of mechanical jointing. My deductions were published in 1927.[21] Subsequently, Balk's presentation of Cloos's methods led me to re-examine the facts, especially with reference to the distinction between compression joints and tension joints and also with regard to the significance of flow structures. This study was made in co-operation with Professor A. C. Waters, of Stanford. Shortly thereafter Dr. Walter H. Bucher at my request courteously examined the quarry and reached independent conclusions, which I am at liberty to quote.

Study of the joints in the granodiorite of Logan quarry was based upon different assumptions at successive times. In 1924 it was thought that all smooth well-developed joints were produced by compression. And when the analysis, made according to mechanical principles, indicated an initial pressure in an east-west direction and also a later pressure in a north-south direction, the evidence was accepted. The subsequent application of Cloos's methods led to the conclusion that the system of joints from which an east-west pressure was deduced was an effect of tension. The inference, based upon a mistaken assumption, was consequently erroneous. The east-west pressure was not in evidence and presumably had never existed as a deforming stress. On the other hand, the inference, also reached in 1924, that a north-south stress had caused shearing and jointing was confirmed by later studies, all the facts bearing on the question being taken into consideration. Those facts are as follows:

The joints in the granodiorite of Logan quarry, as observed in the field, appear to fall into five classes. Enumerated in the order of obviousness they are: (1) master-joints, distinguished by general occurrence, planeness, extension in strike and dip, and rectangular attitudes with reference to conjugate shears; they are here attrib-

[21] B. Willis, "La Force seismique en Californie," *Livre jubilaire Société géologique de Belgique* (1927), pp. 411–62.

uted to compression; (2) joints filled more or less irregularly with aplite, exhibiting well-defined walls, are occasionally extensive, but tend to branch and play out, as where thick veins spread into many little ones; they are ascribed to tension; (3) joints occupied by a basic intrusive, formerly called basalt, but identified by Waters as lamprophyre; (4) minor joints, of little extension and more or less irregular

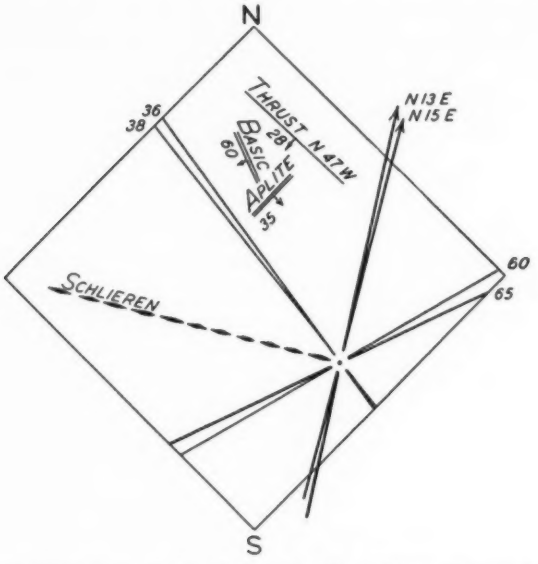

FIG. 5.—Logan quarry. Horizontal plan of schlieren, joints, dikes, and thrusts in granodiorite.

development, cutting across corners and branching into large blocks; and (5) thrust planes, which cut across earlier systems and offset dikes.

We may interpret these several structures in the order named as evidence of the stresses of which they are presumably the mechanical expression.

Joints of class (1) are regarded as shearing planes, due to compression. The source of the stress is assumed to have been within the batholith (i.e., a movement of the mass toward this particular area)

or extraneous to it; in any case outside the body exposed in Logan quarry. It is thought to have been a general orogenic pressure, affecting the region as a whole. On observing the attitudes of these major joints, it is found that they form sets of four planes, arranged in two pairs. In each pair the two planes have nearly parallel strikes but divergent dips, from which it follows that the ridge-pole intersection of each pair is nearly horizontal and that the strikes of the two sets embrace very nearly the true angle of divergence of the conjugate joints (Fig. 6; isometric projection of the joint planes, *A*, *B*, *C*, *D*). It also follows that the direction of pressure was nearly horizontal or nearly vertical, not oblique.

When plotted in a horizontal plane, the strikes of the two pairs are seen to intersect in slightly obtuse and slightly acute angles, and the same is true of the opposed dips when they are projected upon a vertical plane. Either the acute angle or the obtuse angle was bisected by the line of pressure. The possible bisectrices lie at right angles to one another. Unfortunately, geologists are not agreed as to which should be accepted as indicating the true direction of the stress of compression. A view of which Bucher is an exponent (1921)[22] holds that the stress bisects the acute angle in rocks, as it does in brittle substances. Where rocks are brittle, are like concrete in a testing machine, that deduction is correct. But it may be reasoned that a rock under excessive confining pressure, especially when solidified at high temperature, is not brittle; rather is it plastic. It will yield plastically before parting on shearing planes. The planes of potential shear will be spread before the partings or joints develop and will embrace an obtuse angle, which will be the one that should be bisected to obtain the direction of the effective stress.

Proceeding on the assumption of the obtuse angle, I obtained in 1924 the bearing N. 16° E.–S. 16° W. for the direction of the compressive stress in a horizontal plane.[23] Analyzing the dip angles according to the same principle, I found that the line of stress was directed upward toward N. 16° E. at an angle of 9° with the horizontal. In other words, it pitched 9° toward S. 16° W. As the stress

[22] W. H. Bucher, "Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. XXIX (1921), pp. 1–28.

[23] Willis and Willis, *op. cit.*, Appen. II, pp. 456–58.

could not well have originated in the outer skin, near the surface of the earth, it must have come from below, from under the continental margin or from beneath the Pacific. On reviewing this evidence in

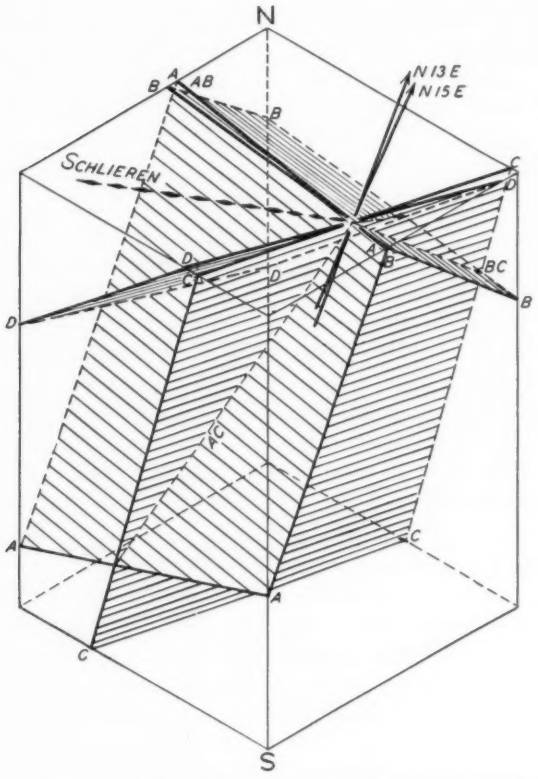

FIG. 6.—Logan quarry. Isometric projection showing relations of schlieren, two sets of conjugate joints attributed to compression, and the direction of pressure deduced from them.

1936, I made independent observations for strike and dip of the joint planes and, on plotting them, I obtained for the bearing of the stress the value N. 15° E. (see Figs. 5 and 6).

To conclude this phase of the problem, we may consider the evidence of flow structures, as presented by the arrangement of

elongate bodies. While the granodiorite of Logan quarry is in general homogeneous and not obviously gneissoid, it does contain segregations of the dark-colored constituents, which are flattish and have fairly well-defined attitudes. Their dimensions are up to 30 cm. (1 ft.) in length and a few centimeters in thickness. Three swarms of them occur in the northwest-facing wall of the quarry, and the strikes of their longer axes are, respectively, N. 60° W., N. 75° W. and E.–W. The mean is N. 75° W. The groups are within a few feet of one another, and the mean may be taken as representing their common trend. It was long ago shown by Van Hise and Leith that the orientation of bodies in a flow structure is normal to the pressure. Applying this principle, we get a stress or pressure directed toward N. 15° E. The close agreement with the bearing deduced from the joints is a coincidence, but the general correspondence is significant. The dip of the segregated lenses is not capable of exact measurement in the quarry, but it is very steep and toward the north. Pressure in a direction normal to the flow may therefore be said to have ranged upward from the south, but at a very low angle.

It thus appears from the analysis of conjugate shears and from the observations on flow structures in the granodiorite that the pressure which impinged upon the mass exposed in Logan quarry at the time of intrusion and subsequently up to the time when shearing occurred was directed about N. 15° E. and dipped at about 9° toward the south.

Before leaving Logan quarry, we have to consider the other groups of joints enumerated above. They include those which are filled with aplitic or basic dikes. The aplite filling is regarded as having risen during a late stage of intrusion and to indicate that the joints it occupies were primary structures. In 1924, when I regarded them as effects of pressure from west to east, I explained the intrusion of the vein material as evidence that the squeeze on the deeper, still-molten part of the magma was more intense than the unit stresses upon the solidified portion; therefore, the aplite had been forced in. That there is excessive pressure upon the base of a deep magma column, which extends down into overloaded, incompetent rocks, is demonstrable.[24] In this case, however, we do not have to appeal to

[24] B. Willis, "East African Plateaus and Rift Valleys," *Carnegie Inst. Washington Pub. 470* (1936), p. 79.

that condition. On the evidence of the flow structures in the granodiorite we must recognize that the pressure was not east-west, but north-south, during the intrusion of that batholith. Any east-west stresses were tension stresses.

If the east-west tension stresses had been effective during the intrusion of the aplite, we should expect to find the aplite veins ranging north-south, at right angles to the tension; but that orientation is not common. They are more often found occupying joints on the strike of one of the conjugate shears. Hence we may infer that the mass had already solidified and become jointed when the aplite was intruded. It was a large body, divided into wedge-shaped blocks of relatively small dimensions, subject to pressure in one horizontal direction, tending to elongate by separation of the blocks in another horizontal direction, and also tending to yield by moving upward toward the free surface. The angular blocks shifted and rotated. The freedom or difficulty of movement was very local. The tightness or looseness of joint planes was an accident of situation. The aplite intrusions occurred accordingly, where locally favored, and irregularly.

Although the aplite veins thus indicate facile partings, other indications demonstrate intense friction on planes in other orientations. The latter exhibit gouge and even mylonite, thus proving the effects of displacement under intense pressure.

Passing over the minor joints, which are so lacking in systematic relations as to prove that they are due to localized stresses resulting from friction and rotation within the disjointed mass, we may consider the more regular thrust faults. Two well-defined thrusts appear in the quarry face, cutting through and displacing the smaller of two basic dikes, but not affecting the larger one. The offsets are distinct, as are also certain branches or minor thrusts diverging upward from the major plane or sole. The displacement is thus taken up by the branching (see Pl. I). It is evident from the displacement on the thrusts that they represent a definite stress, though one of no pronounced effect. The strike of the thrust planes is N. 47° W., and the dip is 28° SW. If the displacement was directly up the dip, the pressure was directed toward N. 43° E. and upward from the southwest. The bearing lies in the same quadrant as that of the original pres-

PLATE I*a*

Logan Quarry, Massive Granodiorite with Aplite Dikes in Tension Joints

PLATE I*b*

Logan Quarry, Granodiorite Intruded by Lamprophyre Dikes
Which Are in Part Offset by Low-Angle Thrusts

sures, but diverges 30° from N. 15° E. This may be due to local rotation of stresses or to a more general change, but the broad implication of origin remains the same.

Thus it appears that pressure was exerted against the mass of granodiorite in Logan quarry from an early epoch of intrusion and solidification, through the episodes of intrusion of aplitic and later basic dikes, and into some more or less later period, when the thrusts resulted. The general direction of pressure was gently upward from S. by W. toward N. by E. More specifically the original stress may be placed as having been directed toward N. 15° E.

This manuscript had already been cast in essentially its present form in 1936, when opportunity offered to invite the attention of Dr. Walter H. Bucher to the interesting structures of Logan quarry. As a critical colleague, intimately acquainted with the studies by Cloos of the structures of batholiths, his opinion of the significance of the facts carries much weight. He kindly embraced the opportunity with enthusiasm and made a series of independent observations.

Presently there appeared a difference of method, which is not without general interest. It was obvious to both of us that the joints in the granodiorite were of various kinds and of different degrees of importance. They could be sorted in the quarry and measurements for strike, dip, and other relations could be limited to those that appeared to carry weight in the problem under consideration, whether for or against any hypothesis. That was the method I had pursued. Or measurements could be made on all possible joints, and the assembled data could be sorted afterward, in the office, according to their mathematical orientations. Dr. Bucher did this. He observed systematically and thoroughly throughout the exposures and measured 117 joints. From these he selected 87, which he divided into six groups. As he expects to include the discussion in some future paper, I will not anticipate, but may quote the summary of his conclusions, which he has courteously furnished me. He wrote:

Summary.—1. Xenoliths, aplitic dikes, and two systems of joints point consistently to a principal compressive stress aligned notably north-south during the formative stages of the intrusion. 2. After a later intrusion of a thick and several thin lamprophyre dikes, three systems of joints seem to have formed, which seem to be due to a doming of the granite region along NNE

and WNW axes in the trend indicated by the much faulted syncline just south. One system of faults is clearly due to the drag along a NE-trend fault, one of many that cut the syncline referred to.

Bucher's first conclusion, namely that the "principal compressive stress was aligned notably north-south during the formative stages of the intrusion" is that to which the facts point most definitely. As to the significance of the joints which he attributes provisionally to doming and nearby synclinal folding, we are agreed, I think, that the available evidence is not sufficient to justify a positive opinion.

An interesting suggestion or possibly a check on the inferences from the joint structures follows from consideration of the relative displacements attributable to vertical or horizontal components of the pressure on the rift.

If we visualize the pressure rising at the low angle of 9° and impinging upon the fault plane at an angle of 45° in the horizontal plane, we may deduce the vertical displacement in any movement as equivalent to the tangent of 9° and the horizontal shift as the tangent of 45°. Their ratio is as 0.16 to 1 or as 1 to 6. We would expect that the vertical and horizontal movements had that relation in any actual faulting during the early stages of development, when the jointing was produced. We might hesitate to infer that the same relations had persisted from that remote pre-Eocene time down to the present. And yet the relative movements, vertically and horizontally, in the earthquake of 1906, were approximately of the same proportions, as 1.5 to 10 feet (0.15 to 1) more or less. The close quantitative relation is, presumably, coincidence; nevertheless, the general qualitative persistence of the stress appears to be an impressive fact.

A check on the observations made in the Logan quarry may be had by an examination of the batholithic mass of Montara "granite," situated about 35 miles north of the Logan body and in a similar position, west of the San Andreas Rift, though not immediately on the fissure. The Montara was mapped and described by Lawson[25] as a pre-Eocene intrusion of quartz diorite, which varies in the proportions of hornblende or biotite and in that of plagioclase, and which also contains small veins of aplite and pegmatite. It is petro-

[25] "Geology of San Francisco Peninsula," *op. cit.;* "San Francisco Folio," *op. cit.*

logically similar to the rock at Logan quarry and appears to belong to the same period of intrusion, though probably independent as a superficial mass.

Jointing in the Montara batholith is very obvious, but too complex and too badly weathered to be useful for mechanical interpretation, unless, possibly, after an exhaustive study.[26] The veins of aplite range northeast, northwest, and nearly north-south. They resemble those of Logan quarry in orientation and also in feathering-out in the manner characteristic of tension fissures. They suggest approximately east-west elongation by separation of joint blocks, as in the other case. The mylonite is developed on steeply dipping surfaces that strike nearly east-west, suggesting north-south pressure, and certain thrust planes striking nearly north-south exhibit striae that dip 40°–46° toward the south. The joint blocks were thus displaced diagonally upward under oblique compression. These more or less suggestive and coherent facts were recently observed in the cuts made for the railroad in the cliffs along the bold coast. But though the data are suggestive, they would not in themselves be conclusive as to the true direction of pressure upon the granitic mass. There are, however, more satisfactory evidences.

A condition of normal gravity faulting and definite elongation can be observed in certain aplite veins. The direction of the stretching is approximately N. 80° W.–S. 80° E.

In an aplite dike which is locally 10 feet thick conjugate joint planes, which are very sharply developed and not weathered, strike, respectively, N. 70° E. and N. 25° W., both planes dipping vertically. They embrace the obtuse angle of 95° with a bisectrice bearing N. $22\frac{1}{2}$° E.

Finally, it is to be noted that the quartz diorite of this locality, Montara Mountain, exhibits numerous segregations of dark minerals and locally shows a slight development of gneissoid banding. These are flow structures and may be regarded as lying with their plane normal to the dominant pressure at the time of the intrusion. The strikes of these flow structures are observed to bear N. 80°–90° W.

[26] R. B. Morrison, "Primary Internal Structures in the Northwestern Portion of the Montara Stock, San Mateo County, California" (unpublished thesis, Stanford University).

The mean is N. 85° W., and the dip is about 80° toward the north. From these observations it appears that the pressure at the time the structure assumed this orientation was directed upward, at a low angle, toward N. 5° E.

The internal structure of the Montara granodiorite has recently been studied by graduate students at Stanford, Mr. R. B. Morrison and Mr. J. W. Ambrose. From a detailed map prepared by the latter it appears that the flow structures in the central part of the batholith trend in one group N. 60° E. and in another, situated farther southeast, N. 60° W. They are not regular in orientation but exhibit these bearings in a general way.

Mr. Morrison has prepared a thesis from which, with his permission, I quote the following excerpts. Under the heading, "Flow Structures," he says:

> Considering the interior phase as a whole, the general orientation of the flow planes is about E.–W. with groups striking as much as N. 60° E. and N. 60° W. Though this general trend of the planar structures seems well expressed, local variations are common, as the flow surfaces themselves are characteristically undulatory in strike and dip.

In describing the systems of joints and dikes, Morrison distinguishes between "transverse" and "longitudinal," i.e., approximately normal to and parallel with the elongation of the intrusive body. Regarding the transverse system he states:

> The most prominently developed system of joints in the area has a mean strike of about due N. to N. 15° E. and is vertical or steep in inclination. In the more northerly sections some of these joints have been intruded by pegmatite dikes. [The pegmatites had been called aplite prior to microscopic examination, and I have retained that field name.]

These I would regard as tension joints, oriented approximately parallel to the direction of maximum compression, and we are, I understand, agreed in that opinion. They may also be regarded as effects of internal rotational shear, possibly controlled in direction by the earlier tension joints.

Concerning the "longitudinal" joints I quote:

> Apparently contemporaneous with the pegmatitic dikes of the transverse system is a series of pegmatitic dikes which averages about N. 75°–80° E in strike and 80–85° N. in dip. In the more southerly sections by far the greater number of the dikes belong to this latter system. Not only are they abundant here but

they are often wide (frequently 6 inches or more in width, 12 feet being the maximum observed). These larger dikes usually show closely spaced internal jointing, parallel to the walls, possibly due to shearing, secondary in nature, which has frequently affected them in this direction.

In addition to the secondary shearing many of the wider dikes present a megascopic appearance, which (though it should be confirmed by petrographic study) is as if they were multiple injections, which had suffered some longitudinal shearing of a different nature, possibly contemporaneous with their formation or at least while they were still at an elevated temperature.

Morrison sums up his conclusion with reference to the conditions of pressure by saying:

Since one of the two major steeply dipping joint-dike systems in the Montara mass is parallel to the elongation of the intrusive and the other is transverse to this, a combination of lateral pressure and vertical stress, with the latter dominant, seems to be indicated for the closing stages of the intrusive epoch.

In reaching this conclusion, Morrison cites the experiments by Hans Cloos,[27] which show that

in elongated intrusions a dominantly vertical stress causes orientation of most of the earlier dike-filled joints parallel to the longer axis of the body, while with a combination of lateral pressure and vertical motion a majority of the joints develop transverse to the long axis.

Morrison's observations were made in greater detail than mine and yet developed no material differences of fact. We are also agreed as to the directions of compression and elongation of the mass of granodiorite, deduced from our independent studies. Yet, as indicated above, there is a difference of interpretation, which I deem worth stating, slight though it may be. It relates to the dynamical condition of the stock at the time of intrusion of the aplite solutions.

According to the description and illustrations of Cloos's experiments in the article cited, the material upon which he experimented was of the nature of a thick, continuous layer; it was not jointed; it did not consist of discrete blocks. The granite, per contra, appears to have been already jointed and to have been traversed by numerous parting planes before the aplite solutions rose into it. Pressure upon those veins of invading solution was hydrostatic and must have been transmitted equally in all directions. If so, we can hardly speak

[27] "Einige Versuche zur Granittektonik," *Neues Jahrb. für Min., Geol., und Paleont.*, Band LXIV (1930–31), pp. 829–36.

of one stress or another as having been greater. We may, however, recognize that the resistances were unequal and that the movements would be more or less freely, more or less obstructedly, directed toward the least resistance. With this qualification, we may agree that the movement was presumably upward, since the resistance of the cover would be less than that of the sides. The difference of statement may not seem significant, since the conclusion is the same; but it bears upon the internal structures, which, according to the view that visualizes an agglomeration of angular blocks buoyed up by the invading solution, are a result of internal, local displacements, involving translation and rotation of discrete bodies of no great size. The concept has been stated in discussing the structure of the Logan quarry granite.

It thus appears that the cumulative evidence of flow structures, shearing under compression, and mechanical elongation indicates that the Montara batholith, during and for some time after its intrusion, was subjected to pressure directed from slightly west of south toward slightly east of north, in a manner and with a bearing closely parallel to the pressure exerted upon the Logan batholith. If the two intrusions were produced during a common geologic effort, it is probable that the stresses were practically contemporaneous.

If it may be regarded as established that the Logan and Montara stocks experienced a stress of the character and bearing indicated above, we have next to inquire whether that pressure was properly oriented to cause shearing in the direction of the strike of the San Andreas Rift. The average strike is N. 46° E., and the deduced bearing at Logan quarry is N. 15° E. The enclosed angle is 61°, or 16° in excess of the mathematical value of 45°. If we consider more strictly local conditions, we find that the strike of the San Andreas fault at Logan quarry is N. 51° W., following the outline of the batholith. On the other side of the fault, northeast from the granite, is a squeezed mass of Miocene shale (Monterey), which in the relative, strike-slip movements has been displaced southeastward past the granite. The drag has been such as to rotate the granite in a clockwise direction and thus to increase the angle between the bearing of the stress, which was inferred from the structure in the granite, and the strike of the rift. The amount of rotation due to

drag alone may be that indicated by the angle of 16°. To it may be added the effect of local divergence of the shear from its average strike, to give us the total angular discrepancy of 66° between N. 51° W. and N. 15° E.

In the case of the Montara stock the bearing of the stress inferred from the observed structures is N. 5° E. or within 6° of the mathematical figure, diverging from the average strike of N. 46° W. of the rift. But, on approaching the Montara stock from the southeast, the rift bends toward the north, and the strike for a long distance is but N. 35° W. Thus the local relation would be that of an angle of only 40° (35 + 5) between stress and shear. This means a rotation of the stress, that is, of the Montara batholith toward the west, anti-clockwise. Such a rotation seems quite probable when we consider that the batholith is an oval body, with longer axis trending northwest, and thus occupies a position in which the pressure would tend to give it an anti-clockwise twist. It is also consistent with the strike-slip and thrust developments on the Pilarcitos fault. An absence of drag, such as appears to have occurred on the Logan body, may be explained by the fact that the Montara does not extend to the strike-slip zone of the rift at the surface, the two being separated by a strip of sedimentary formations, and presumably does not do so in depth.

Thus it appears that, when due allowance is made for local conditions, the angular relations of stress and shear approximate those required by the law of shear as nearly as may be expected in heterogeneous terrains.

A RESIDUAL QUESTION

The body of evidence tending to show that a powerful stress had been exerted to produce the observed deformation of the coastal region of central California, with orogenic effects and during several geologic periods, appeared to me so strong that it displaced other working hypotheses in my immediately active list and demanded further consideration. I particularly noted that the direction of stress was not what I had long assumed. It was and is diagonal to the continental margin, not normal to it.

All my previous speculation had rested on the tacit assumption that the orogenic pressure must be directed at right angles to the

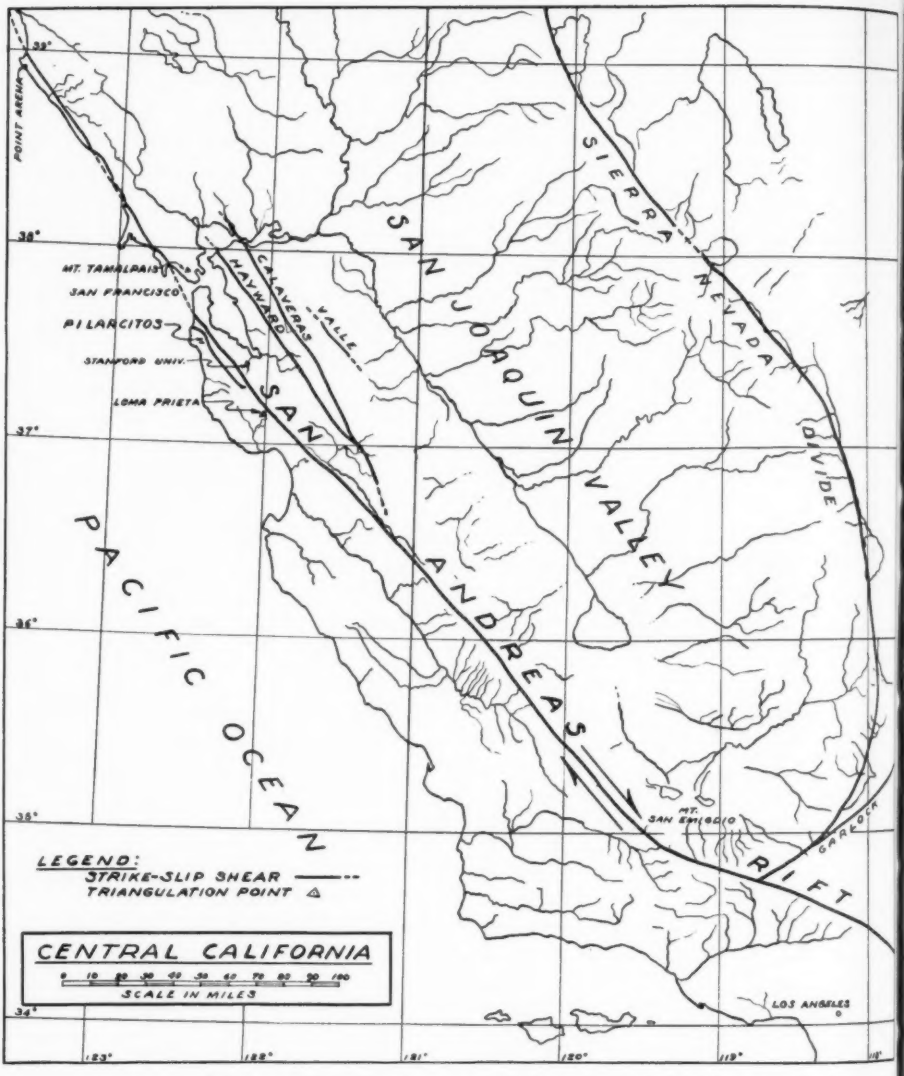

FIG. 7.—Outline map of San Andreas Rift in central California

structural axes, must be what we now recognize as nonrotational stress. The concept goes back to Appalachian structure, with regard to which it is true.[28] Reasoning accordingly, I have postulated pressures normal to continental margins, where there are coast ranges, and have inferred causes which might produce the observed effects in that way. Here at least is one case that does not fit the hitherto exclusive assumption. It points to some unknown condition, of indeterminate significance, and therefore demands attention. In the effort to pursue the problem, I turned to southern California, where similar, but still different, structures are known. What I learned there during recent studies which supplemented earlier reconnaissances is the subject of a succeeding paper.

[28] R. T. Chamberlain, "The Strain Ellipsoid and Appalachian Structures," *Jour. Geol.*, Vol. XXXVI (1928), pp. 85–90.

CAVES IN THE GALENA FORMATION

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ABSTRACT

The cave systems commonly are reticulated patterns, faithful delineations of the joint system of the formation, with no integration toward a trellised subterranean drainage pattern. The distribution of the lead and zinc ores gives no indication of any former lower water table. Four levels are known in the Dubuque caves, the lower two full of water until pumped out during the mining operations. Only one of the caves described contains a stream today or shows evidence of ever having contained one. There is good evidence in this cave that before the stream entered there was only a reticulated three-dimensional network of solution-widened joints such as all the others described still are. It is concluded that each cave system has been made by solution below the water table and that only one of these has later been modified by a vadose cave stream.

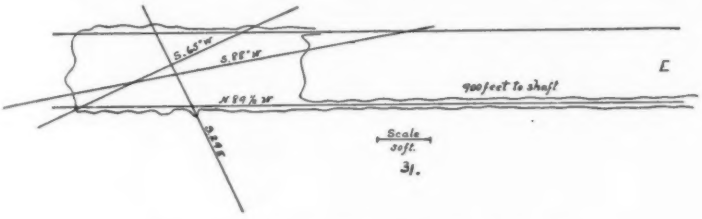
Caves in the Galena formation which are known to the writer are essentially all along joints. Vertical dimensions almost invariably are several times the width, with a maximum of about twenty times. Galena caves are commonly too narrow for the free passing of two lines of visitors. Wide chambers occur only where two or more joints meet at low angles. The maximum reported height of chambers is 70 feet. Roof collapse is not common, and therefore prevailingly the original roofs are present.

Caves in the Galena formation have been studied in Illinois, Iowa, and Minnesota. They are numerous in the vicinity of Dubuque, Iowa, where many in the upper part of the formation were explored and mined for lead and zinc several decades ago but are now unenterable. All those mapped and described[1] at that time consist dominantly of long, straight, narrow passages, oriented nearly east-west in close-set near-parallelism, with minor north-south intersecting passages of similar proportions and usually a few still tighter passages, also similarly proportioned, on "quartering" joints. Usually a cavern group is in one horizontal plane, elongated along a "range." A range is an east-west group of "crevices" (joints en-

[1] A. G. Leonard, "Lead and Zinc Deposits of Iowa," *Iowa Geol. Surv.*, Vol. VI (1897), pp. 11–66; Samuel Calvin and H. F. Bain, "Geology of Dubuque County," *Iowa Geol. Surv.*, Vol. X (1900), pp. 379–652.

larged by solution). They appear to occur in the structural sags, strike parallel, and avoid the few named anticlines of the region. The "Timber Range" crevices were traversable (after opening by mining) for 5 miles, and the parallel members, with intervening rock, had a total width of only 100 feet.

Four levels were worked during the mining heyday, the lowest two only by pumping. These lower levels were found by following down "chimneys" from the uppermost level. Chimneys occurred at the intersections of master and minor joints. Caves on the lower levels occurred along the same joints as the uppermost chambers. Many "chimneys," however, were simply high narrow cones in the cave or



Sketch map showing crevices which form the Stewart's cave.

FIG. 1.—Stewart's Cave, Dubuque, Iowa

crevice roof, there being no opening through to higher chambers or to the surface. All reports agree on the stratigraphic control of these levels. All agree that the main and uppermost level's openings generally came up to and stopped at the "cap rock," though a few chimneys penetrated higher than this, in rare cases up to the base of the Maquoketa shale. The cap rock is a persistent hard layer about 4 feet thick, readily recognized by the miners, occurring 40–50 feet below the top of the Galena formation.

Widths of caves increased abruptly and notably where a series of joints intersected. Stewart's Cave chamber was 80 feet wide and 200 feet long, all an open cave when first entered, because of the intersection here of five joints. The room was rectangular, the two long sides joint-determined (Fig. 1). These two east-west joints continued, at one end, as crevices filled with dolomitic sand. One of them was excavated for 900 feet in the mining operations, its width

between limestone walls ranging from 14 inches to 3 feet. It was stoped out to a height of 25–50 feet, and excavation went down 40 feet in the sand filling without finding any sign of rock bottom.

All crevices (caves) contained fill, the upper one generally the most. The fill is commonly described as "soft dolomitic sand." Fallen fragments of limestone were found embedded in this sand, also lumps of galena. There is little mention of clay fill in these crevices.

"Key rocks" figure prominently in the descriptions of the caves. They may be islands or pillars (Fig. 2) but more commonly are a

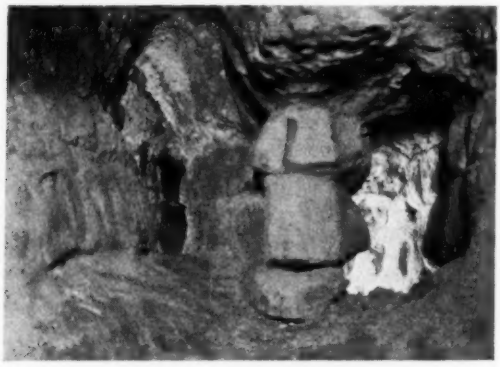


FIG. 2.—Pillar in Crystal Lake Cave (*J* in Fig. 3)

feature of the end of a chamber where the rock between two close-set parallel joints has not all been removed. Key rocks also occur in roofs. In both Kane Brothers and Karrick mines, excavation of the cave fill showed a key-rock floor, the opening continuing downward as two parallel crevices, the rock between them being wider than the sum of the crevice widths. Thus roof and floor topographies may duplicate each other.

CRYSTAL LAKE CAVE

This cave, a few miles south of Dubuque, is mentioned in the literature as one of the region's "crevice" systems. It proved barren of ore. A small part of it is now opened to sight-seers. All accessible parts have been explored and mapped in this study.

The pattern is self-explanatory (Fig. 3). It is a network in one plane, developed along the joint systems. The east-west passages are consistently the widest and highest, the quarterings are consistently the narrowest and lowest, and consistently each passage maintains its particular width, in some cases for hundreds of feet. Commonly the quarterings have roofs several feet lower than those of the main east-west chambers. The ceilings are low throughout the system, and head room for visitors in the opened part of the cave is secured

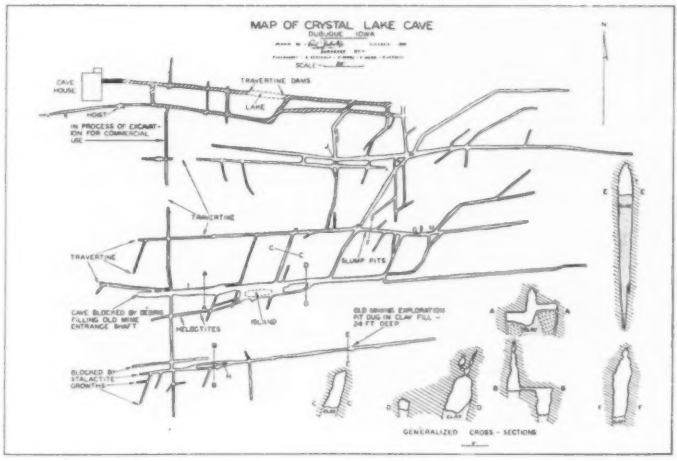


FIG. 3

by excavating trenches for footpaths, as much as 3 feet deep, in the fill. This excavation has revealed the tops or ceilings of several north-south and quartering routes that are entirely filled. There is doubtless a proportionate number of such concealed members of the system in the undeveloped part of the cave. How the bottoms of the different members are related would be very interesting to know. In a vadose-water cave system, deepening should be accompanied by concentration of the drainage, integration of routes, and abandonment of some of the minor early ones. In Crystal Lake Cave, there are more, instead of fewer, members of the system at lower levels, as far as shown.

Endings of chambers as shown in Figure 3 are due to (1) travertine dams, (2) cave-in of an old mining shaft, and most commonly (3) meeting of the roof and the surface of the cave fill. Thus, there is more to the system than could be mapped, for some chambers are filled to the roof. There are no blank-wall endings of chambers like some of those described in the old mine workings. A known, but not now enterable, westward extension of the avenue with the mine shaft blockade is a quarter of a mile long.

The chambers are so narrow in many places that one must walk sidewise. Height in most places is not adequate for erect walking. Proportions in a few places are shown in the cross section on the map, *C–C* and *F–F* being average. *E–E* is a special case, a cross section in which it was possible to show extent and proportions of the filled part as well as of the empty chamber. A shaft had been dug here sixty years ago, in search of ore, and was entered in this study by block and tackle and bosun's chair. The gradual downward narrowing to become a slot at the bottom is significant of conditions of origin of the chamber or crevice. With data from some of the mine workings, as reported in the literature, it indicates that the cave floors known in the region are far from stream-determined floors.

The fill revealed in the walls of this old shaft is a brecciated clay. Only the top 2 or 3 feet of the 24 feet of depth showed stratification. Traces of lamination exist in the crumb- and granule-sized blocks of the breccia, also minute slickensides here and there. There are no pebbles, sandy lenses, or layers, or traces of their ever having been in the deposit. Contact with wall rock is through an inch or so of dolomitic sand, obviously formed by solution of the dolomite since the deposit was made. Actual rock bottom is not visible now, but a few inches of dolomitic sand occur under the clay. The brecciation is imputed to settlement in compaction of the clay. It may be that fill once reached to the roof and that the open chamber is a measure of the total settling, the compaction amounting to about one-fifth of the original thickness. But the dolomitic sand margining and underlying the clay indicates solution of dolomite since deposition, a cause for some of the settling.

Roof features are enough alike throughout the cave to allow gen-

eralizations. Flat roofs, due to falling of slabs, are rare and limited to places where two joints converge at a low angle, the thin edge of the separating wedge having suffered removal to produce a wide place. A "key rock" may remain in such wides, it being the lower part of the edge of the wedge. Almost wholly, the roofs are original and preserve the solutional patterns. Pockets (somewhat resembling irregular potholes upside down) are common (Fig. 4), some of them so complexly and irregularly developed that they penetrate into one another and produce arches and bridgings. Solution to make these roof pockets occurred only because the cave was full of water at all times, not as a vadose stream may in flood time fill it to the roof. Were the latter the case, air would tend to occupy such pockets, and there could be little solution. The upside-down pot-holes are, instead, loci of maximum roof solution.

FIG. 4.—"Spongework" of irregular tubes and pockets in roof of Crystal Lake Cave. Observer is looking directly up (*G* in Fig. 3). Photo by George S. Monk.

A steep gabled roof with gothic arch or window effect, as the walls converge to make the roof, is repeated over and over (Fig. 5). In many cases, the uppermost rude circle of the window is complete, a bridge of stone separating it from the cave below. There are some cases of two windows, one above the other (Fig. 6), and one case of three. Prevailingly, the higher ones are the smaller. In some cases, the windows are tubes several feet in length, suggesting the primitive cave half-tubes which Malott[2] has described. Their diameters range

[2] Clyde A. Malott, "Lost River at Wesley Chapel Gulf, Orange County, Indiana," *Ind. Acad. Sci. Proc.*, Vol. XLI (1932).

from 3 or 4 inches to 12 or even 18 inches. Some complete tubes may, farther along their length, lose their floor and become half-tubes (Fig. 7). Some tubes dwindle in diameter until they apparently end. Not all tubes are horizontal; indeed, some of the vertically oriented roof pockets are really short blind tubes. It appears that earlier in the cave's development, there existed along each joint now opened a series or network or spongework of tubes, the horizontals dominant. As the tubes were enlarged, the separating walls were dissolved away, and the aisles or narrow chambers with steep-gabled gothic arched roofs were left.

FIG. 5.—Gothic window profile common in chambers of Crystal Lake Cave. Remnants of two tubes at the top.

Let the reader recall the mine cave system, with chambers at three and even four different levels, along the same joints in general, but (except for a few chimneys) separated by tight rock. Note the conviction of Leonard and of Calvin and Bain that the different levels were determined by stratigraphy, the openings formed in more soluble layers. Consider the Crystal Lake system again, developed in one stratigraphic plane, its chambers narrowing upward into gabled roofs with remnants of smaller and smaller tubes and narrowing at the bottom in the mining shaft. Add to this the downward dividing of a cave chamber on both sides of a key rock found in some of the mines. Observe that in all these caves of the Dubuque region there is no suggestion of the beginning of a trellis branchwork system, there are no dominant passages, no rounded corners at the right-angled turns. No cave stream has used the aisles of any Dubuque cave unless it filled them all at the same time and in that remarkable anastomosis, it widened each set of barely open joints to a uniform

amount for each system, most for the east-west joints, least for the quarterings. Even one of Swinnerton's water-table streams[3] could hardly make this remarkably uniform result.

Furthermore, the cave lies 50–75 feet below the Galena topographic platform, apparently identified by Bain as a part of the defunct Lancaster peneplain, and not more than a mile north of a higher ridge or spur of the summit peneplain held up here by Niagara dolomite. There is less than a square mile of drainage area from which groundwaters could be drawn for any water-table stream here during the dissection of the Galena platform. Such a stream, if it existed, should have flowed north, from higher land to lower, as do the surface streams trenched into the platform. The dominant chambers are elongated at right angles to the direction of surface drainage.

FIG. 6.—Two windows above the cave chamber, Crystal Lake Cave (larger chamber of section *D–D*, Fig. 3). Photo by Arthur Gale.

The other cave systems of the Dubuque region, explored in mining, are too closely spaced to have all carried anastomosing water-table streams. Though the dominant chambers lead east toward the Mississippi trench in a suggestive way, only one was ever entered from the valley slope and none was ever traced out to the valley walls. In the Galena, Illinois, mining district, east-west chambers also are dominant and are unrelated to any deep valleys which could take discharge from them. One group, crossed by a north-south valley, was entered from the valley bottom through shafts that go

[3] A. C. Swinnerton, "Origin of Limestone Caverns," *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932).

65 feet deeper to reach them. Surface valleys are not genetically related to the crevices.

Many of these crevices are (or were) crystal-lined caves, lead and zinc sulphides predominating. Much of the mineral was found attached to the roof and in chimneys and pockets in the roof. Many walls were originally covered with the sulphides. Galena occurred in largest quantities in the upper levels, with some smithsonite but no sphalerite. Smithsonite was most abundant close to the water table, more of it above than below, and extending farther above than below. Sphalerite occurred only in the lower levels, below the water table, and was obtained only after pumping out the cave, lowering the water as much as 60 feet. Some vugs and vein centers in the sphalerite were filled with crystalline calcite. The testimony of Calvin and Bain is that, except for the contained ores, the caves of the lower water-filled systems are like those of the air-filled systems above.

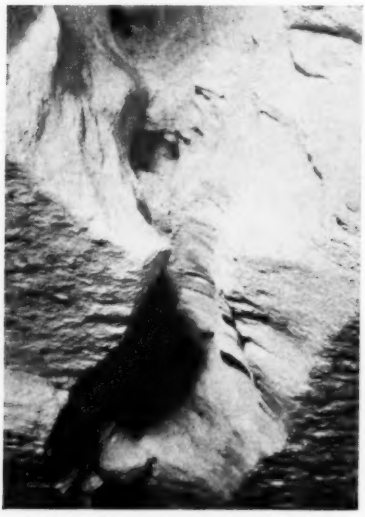


FIG. 7.—Half-tube and associated pockets in roof, Crystal Lake Cave. Observer is looking upward at an angle of about 45°. Fall of roof slabs has made a half-tube at this place. Photo by George S. Monk.

All authorities agree that this vertical distribution of the minerals is largely secondary, due to the lowering of the water table in the present erosion cycle. Sphalerite is less stable than galena and has altered to the carbonate and migrated down as the water table lowered. Galena has survived, even occurring as float ore in the soil. But there is a recurring opinion that more galena than found was originally deposited in what are now the air-filled levels.

All agree that the chambers were full of water when the ores were introduced. Three different types of circulation for the original

deposition have been proposed: (1) descending meteoric waters, (2) artesian meteoric waters, escaping where the once-overlying Maquoketa shale was eroded through, and (3) rising magmatic waters.

All agree that deposition of ores in these joint crevices (caves) was preceded by solutional enlargement and that there has been essentially no replacement in the deposition. But authorities rarely commit themselves as to whether the same circulation which brought in the ores did the dissolving. Much suppositious and involved chemistry has been written on the subject of deposition of these Wisconsin-Illinois-Iowa ores. On one item of this chemistry all agree—the waters were not oxidizing. If they came from the surface at all, they had become reducing en route. And on one physical condition they all agree—the caves were already formed and full of water when the crystal clusters and masses of galena were deposited.[4]

Much of the galena mined in the Dubuque region was found buried in cave clay and sand, associated with limestone blocks, both clearly having fallen from roofs and walls. Much of the falling involved only separation of the crusts of sulphide minerals because of softening of the limestone on which the crusts had grown. So soft and sandy are the present walls and roofs of Crystal Lake Cave that it would be difficult for crusts of any considerable weight to become attached. A quarter of an inch of sand may be scraped off almost anywhere, in some places an inch. This weathering to dolomitic sand has occurred in the caves since sulphide deposition ceased, since the caves were drained. But no notable enlargement has occurred, for extensive crusts still clinging to the walls were found by the miners.

It is therefore concluded that the caves or crevices in the Galena formation beneath the Dubuque region were dissolved out along the joints while below the water table, that no direction or concentration of flow of dissolving water is recorded, and that almost no

[4] Stalactites and stalagmites of galena, pyrite, and sphalerite are reported by a few observers, obviously dripstone deposits made in the presence of air. They are very rare and are younger than the crystal growths. For their formation we need only to have locally determined reducing water, dripping late in the cave history, dissolving some of the ores and redepositing them. The existence of sulphide stalactites and stalagmites does not militate against the concept of phreatic origin of the ores.

alteration (other than clay and sand filling) has occurred in the caves since air entered them as the water table was lowered.[5]

CAVE NEAR MOUNT CARROLL, ILLINOIS

Smith's Cave, in Galena dolomite, is a mile west of Mount Carroll, Illinois, in a privately owned park, a part of the valley of Carroll Creek. The creek here is in a short rock-walled gorge, the result of a drift blockade of the creek's pre-Illinoian valley. The gorge is therefore a transection of a pre-Illinoian stream divide. Its cutting must have lowered the water table along its route.

The cave is entered at the base of a 50-foot limestone cliff, by an artificial opening made half a century ago in the search for lead ore. The prospectors found and followed a clay-filled joint crevice outcropping in the cliff face. For about 50 feet, they had to widen the crevice for passage space. In the roof of this passage and in the cliff outside, the joint shows only a few inches of clay filling between the rock faces.

Beyond this excavated length is a natural cave chamber on the same joint, oriented north 55° east, very narrow, with a clay floor and a very irregular roof. For about half the chamber length, the roof is marked by rough but definite tubes and half-tubes, most of them horizontal but some at angles as high as 45° and descending in either direction along the joint. Solution pockets, or upside-down potholes, are associated with the tubes. In generalized profile, the roof is like that prevailing in Crystal Lake Cave, a steeply pitched gothic window. In two places, irregular vertical passages come down from above, from what might be called an upper level. But the upper chamber has no definite floor. It is separate simply because a portion of the joint was not widened here, so that an irregular bridging exists. The two chambers and two chimneys are only parts of a coarse-grained spongework produced by solution along the joint.

[5] The Mississippi River trench at Dubuque has a Pleistocene fill 300 feet deep. Before the filling, the water table under adjacent slopes certainly was lower than at present and conceivably the east-west crevices could carry the effect of the deep trench on water-table altitude back under the hills well beyond the immediate slopes. But no writer on the genesis of these ores reports any evidence for a former low water table in the vertical distribution of the sphalerite or smithsonite.

The innermost hundred feet of the present cave have been excavated in limestone largely by the prospectors. It follows the same joint, however, and at the end the joint is double, 30 inches of rock (a key rock) separating the two, each of which is rather tight. There is strong suggestion that the joint is a complex of varying number of minor subparallel joints. Convergences of these, divergences, curved courses—all would be factors in determining variations in width and in roof designs.

Smith's Cave is older than the Pleistocene stream valley. Before mining, it had no opening to the gorge near by. It had no continuation, as a cave, in either direction along the joint, and no cross-joint original chamber has been found by which a cave stream could have escaped. The clay fill conceals the egress route of the dissolving water. It descended below present and earlier water tables. The cave is interpreted as a sub-water-table feature which never subsequently had vadose flowing water or a water-table stream in it.

NIAGARA CAVE, NEAR HARMONY, MINNESOTA

This cave occurs in a gently rolling upland 40 miles west of the Mississippi and about 2 miles from the Iowa-Minnesota state line. The region is covered with Kansan drift and with loess, through which a few shallow sinks show, some of them in rows. There are no swallow holes or lost creeks in the vicinity. Upper Iowa River has trenched 200 feet below this upland on the south, and Root River, 10 miles to the north, is 350 feet below.

Except for some small chambers, the cave is a subterranean streamless canyon, zigzagging along the courses of four joint systems in the Galena formation for 2,800 feet, and possessing a bedrock floor throughout most of that distance. The courses between angles are almost perfectly straight. Dominant orientations are east-west, and most departures from this and returns to it are 45° angles.

The roof is progressively higher above the floor down along the gradient of the cave, attaining a maximum height of 70 feet and having a width at that place of scarcely 3 feet. The general cross section is that of a great vertical slot, widened at the bottom in some stretches to approximate the cross section of a long-necked wine bottle. So high and narrow is it in the deeper western part of the

cave that slight sinuosities in the upper part make it impossible to see the roof.

The cave is entered down a small sink, now nearly obliterated in developing the entrance shaft. At the bottom of the shaft, or sink, 65 feet below the surface, a subterranean stream enters from a small lateral chamber, follows the cave floor for 300 feet and then plunges down a well or pit for 42 feet, and disappears into a low, almost untraversable chamber, to reappear in the floor of the main cave at its lower end, half a mile away. Apparently subterranean piracy has taken the stream bodily and entirely out of the long main chamber. Obviously, the unknown part of the stream course existed, as a passageway of some sort, before the piracy at the falls occurred.

Next to the great vertical element in these narrow corridors and the numerous sharp 45° turns throughout the half-mile, the most impressive feature of the cave is the joint continuation in the cave walls at the angles. Looking down more than 50 per cent of the straight vistas of the cave, one sees that the joint continues, the chamber turns. Passing the turn, one looks back to see the same thing for the other joint. Most of these joint continuations are solution-widened, some to 2 or 3 feet, but none to the proportions of chambers. Some of them are empty far back and far up and are very irregular, almost closed here, wide open there, pockety, sinuous in both horizontal and vertical dimensions. Their walls are quite unlike those of the main chamber. And invariably a tight clay fill may be found back in them, though the main cave apparently never has had a clay or sand fill. Similar clay-filled joints outcrop on the sides of the main canyon-like chamber.

Niagara Cave is interpreted as originally a Dubuque type of cave, differing only in the greater heights and smaller widths of the joint chambers, and in the absence of different levels so far as known. It was a three-dimensional network of vertical slots along four joint systems. This phreatic network was then drained as Root and Upper Iowa rivers deepened their valleys and left the upland in greater relief. There was insufficient volume of vadose water under this upland tract to keep all phreatic routes open, and clay entered with the downward-moving waters and filled most of the widened joints. Somewhere up the course of the cave system (not in this known net-

work of Niagara Cave) concentration of surface or subsurface[6] water needed a subterranean route to Iowa River, kept open the series of joints which determine the long zigzag chamber, widened them, and deepened the widened part. The depth (or height) gradually increases to a maximum near the lower end of the accessible part. Apparently this deepening was not so rapid as was the lowering of the water table, but the tight clay fill in the joint for a long time prevented the stream from leaking down into the joint below. Finally, however, leakage did occur, at the site of the falls, and lateral escape was possible along other phreatically enlarged joints for a total detour of nearly half a mile.

Precise details of this shift are not necessary for the argument that Niagara Cave was once a network of narrow phreatic passages, and later was invaded by air and by a small direct gravity flow along selected joints. In the later episode, two additional features were made. Many of the narrow clay-filled slots opening into the vadose cave became widened at the junction, though they remain narrow and filled with clay back in the wall. Also many concave niches were cut in the walls during widening, at places where the cave stream swung from side to side.

Clay-filled joints in the cave floor are required by this interpretation, but nowhere along the great corridor was a good exposure found to show their presence or absence.

Davis[7] in his important paper on limestone caves comments briefly on the Galena caves of Iowa and Illinois, inclining to the view that "the ore-bearing crevices were produced rather deep below the surface of their era, and hence by ground-water solution well below the water table." The writer, agreeing with him, believes also that, except for Niagara Cave, those herein described have never had a water-table stream or a direct gravity stream in them.

[6] Probably surface water. The cave circular reads: "Come when it is raining. The more it rains, the more beautiful is the waterfall."

[7] W. M. Davis, "Origin of Limestone Caverns," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930).

COUTCHICHING, KASHABOWIE LAKE, ONTARIO

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ABSTRACT

The rock assemblage of the Kashabowie Lake area, excluding later intrusives, consists of an altered greenstone series (Keewatin) with adjacent meta-sediments. The age relations are in doubt, though the sediments have been shown as Coutchiching on a previously published map (Kenora sheet).[1]

Field work greatly extended the area of known sediments in Ames and Moss townships. The main greenstone sedimentary contact has been redefined and some sediments discovered on the greenstone side of this contact. Detailed studies near Kashabowie show that interfingering of lavas and sediments does not exist, but thin flows are interbedded with the sediments. The main contact is made by a fault. The fault contact makes age relations difficult to determine, but evidence points to upthrust of the south side, suggesting older age for the volcanics. Major structural considerations favor Knife Lake age for the Kashabowie sediments.

INTRODUCTION

This study consists of the extension westward of the mapping of a sedimentary "mica-schist" series in the Kashabowie area and an investigation of the age of this series relative to that of the adjacent Keewatin volcanics. The area mapped is a part of the northern subprovince of the Lake Superior region and is situated in the district of Thunder Bay, Ontario, about 80 miles west of Port Arthur. It includes Ames and Moss townships and adjacent territory. Two field seasons were devoted to the study—the first to a general examination of the whole area while acting as an assistant on a survey party, and the second, at the suggestion of F. J. Pettijohn, who has emphasized the need of detailed studies of "key areas,"[2] to special study of a rectangular strip extending from the southeastern extremity of Kashabowie Lake westward for 7 miles.

The Kashabowie section of the Thunder Bay district was mapped by William McInnes in 1899,[3] and Moss township in 1927 by R. J.

[1] Map 266A, Ontario, Can., Dept. Mines, *Geol. Surv. Canada* (1933).

[2] "Geology of East Bay, Minnitaki Lake, District of Kenora, Ontario," *Jour. Geol.*, Vol. XLIV (1936), p. 341.

[3] "Report on the Geology of the Area Covered by the Seine River and Lake Shebandowan Map-Sheets," *Geol. Surv. Canada Ann. Rept.* (N.S.), Vol. X, Part H (1899).

Watson.[4] McInnes noted that the area contained mica schists and slatelike schists which he mapped as Keewatin. He also stated: "It is interesting to note that this belt followed westerly along its strike passes into the Coutchiching of Rainy Lake."[5]

Subsequent work to the east by T. L. Tanton[6] has subdivided the Keewatin of McInnes into a volcanic series and a sedimentary series; the latter has been described as Coutchiching. This is of special significance because sediments similar to those mapped to the east occur at Kashabowie and have been shown as Coutchiching on the published Kenora sheet.[7] In addition, the presence of an unfaulted contact between the Keewatin lavas and the meta-sedimentary schists at Kashabowie, reported by Tanton in a personal communication to Pettijohn,[8] gave added significance to the area in the light of the "Coutchiching problem."

As the development of the Coutchiching problem has been summarized by E. L. Bruce,[9] P. L. Merritt,[10] and Pettijohn,[11] further historical treatment of it here does not seem necessary.

Two maps are reproduced; the one (Fig. 1), "Geology of Ames and Moss Townships and Vicinity," shows the area mapped during 1936, and the other (Fig. 2), "Geology of a Portion of Kashabowie Lake and Vicinity," portrays the area of special detailed studies in 1937.

STRATIGRAPHIC AND AREAL GEOLOGY

GENERAL DESCRIPTION AND CLASSIFICATION

The pre-Cambrian formations at Kashabowie as shown on the Kenora sheet[12] are given in the accompanying geologic column with

[4] "Huronian Gold Mine, Moss Township, District of Thunder Bay," *Ontario Dept. Mines Ann. Rept.*, Vol. XXXVII, Part IV (1929), pp. 109–27 (sketch map).

[5] *Op. cit.*, p. 43.

[6] "Eastern Part of Matawin Iron Range, Thunder Bay District, Ontario," *Geol. Surv. Canada Summary Rept. 1924*, Part C (1926), pp. 1–27 (map).

[7] *Loc. cit.*

[8] Pettijohn, "Early Pre-Cambrian Geology and Correlational Problems of the Northern Sub-province of the Lake Superior Region," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), p. 159.

[9] "Coutchiching Delta," *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), pp. 771–81.

[10] "Seine-Coutchiching Problem," *Bull. Geol. Soc. Amer.*, Vol. XLV (1934), pp. 333–74.

[11] "Early Pre-Cambrian Geology, etc.," *op. cit.* [12] *Loc. cit.*

some modifications. The sediments mapped as Coutchiching are regarded by the writer as of questionable age and are accordingly here named Kashabowie sediments. They are known to contain volcanic admixture and therefore are not to be correlated, so far as present information goes, with the Coutchiching series of Rainy Lake described as free from volcanic admixture by A. C. Lawson.[13] As a result of the present study they are provisionally placed stratigraphically above the Keewatin. These sediments may possibly be Knife Lake[14] in age, for they are lithologically similar to the Knife Lake mica schists.

The Keewatin rocks which occupy nearly one-third of the area studied are, in the main, an altered assemblage of volcanics which have been correlated with the Keewatin of the Lake of the Woods region. This correlation has been made by all previous workers within the area and in adjacent areas where similar rocks are found. These greenstones are of "Keewatin type," and their classification as Keewatin is adopted in this study.

The Kashabowie sediments lying to the north of the greenstone series occupy approximately 80 square miles of the area, attaining a maximum width of nearly 8 miles at the western border of the map area. These pre-Cambrian sediments are mainly metamorphosed graywackes, arkoses, and slates. The development of micas and foliation within these rocks has given them a characteristic mica-schist appearance. The original bedding has been well preserved, and the recognition of these rocks as sediments forming a distinct series has not been questioned.

Both the greenstone series and the sedimentary rocks have been intruded by a granite which has been considered to be Algoman in age by Tanton.[15] This correlation is accepted by Leith,[16] and R. T. Chamberlin.[17] The main body of this intrusive is apparently con-

[13] "The Archean Geology of Rainy Lake Re-studied," *Canada Dept. of Mines Geol. Surv. Mem. 40* (1913), p. 5.

[14] The writer here adopts the classification of C. K. Leith, R. J. Lund, and Andrew Leith, "Pre-Cambrian Rocks of the Lake Superior Region," *U.S. Geol. Surv. Prof. Paper 184* (1935).

[15] *Op. cit.*, p. 18*c*.

[16] Leith, Lund, and Leith, *op. cit.*

[17] "Shifting Orogenic Belts of the Southern Canadian Shield," *Jour. Geol.*, Vol. XLV (1937), pp. 663–81.

GEOLOGY
OF
AMES AND MOSS TOWNSHIPS
AND VICINITY
LEGEND
INTRUSIVES
GRANITE
KASHABOWIE SERIES
INTERBEDDED BASIC FLOWS
GRAYWACKE ARKOSE SLATE AND TUFF
VOLCANICS
ACID AND BASIC LAVAS TUFFS AND
UNDIFFERENTIATED BASIC INTRUSIVES
SCALE OF MILES
GEOLOGY BY H.S.PEPROW
1936 & 1937
AMES
MOSS
KASHABOWIE LAKE
SHEBANDOWAN LAKE
BURCHELL LAKE
KASHABOWIE

FIG. 1

tiguous with the Vermilion and Giants Range batholiths to the southwest, which are of undisputed Algoman age.

Dike rocks of basic type cut both the Keewatin series and the sedimentary group. Similar dikes were not observed to cut the granite intrusive. The age of these dikes was not determined, but somewhat similar dikes in the Matawin iron range have been regarded tentatively as Keweenawan in age.[18]

The pre-Cambrian units which have been recognized are summarized in the following geologic column:

Keweenawan?	Diabase dikes
Algoman	Granite, syenite, gneiss, and related dikes
Knife Lake?	Graywacke, arkose, slates, paragneisses, small chlorite schist bands, tuffs, volcanic breccia, and interbedded basic flows
Keewatin	Altered lavas, pyroclastics, basic intrusives, iron formation, and some sediments

DESCRIPTION OF THE KEEWATIN ROCKS

The Keewatin greenstones in the Kashabowie region form a broad southern belt which is made up mainly of lavas of acidic, basic, and intermediate rock types together with some intrusives. The term "volcanics" has been generally adopted in descriptions of these rocks because of the extreme difficulty experienced in any attempt to map the intrusives separately from the extrusives, the whole assemblage having been metamorphosed sufficiently to render separation in the field almost impossible. The rocks are mostly andesitic in nature. They weather to varying shades of green, light apple green being characteristic. In the hand specimen they appear gray green and are commonly fine grained. More basic types weather to darker shades of green, whereas the acid rocks vary from gray to what sometimes appears as pale-green to almost white exposures. Ellipsoidal structures, volcanic agglomerates, and amygdule zones are locally common and yield evidence of the effusive character of the bulk of the series. Chlorite and sericite schists are frequently observed. Diorite

[18] Tanton, *op. cit.*, p. 21c.

and gabbro intrusives and dark basalts are a part of the series. Some banded iron formation, consisting of magnetic iron-bearing bands interlayered with dark cherty bands, gives probable evidence of sedimentary origin.

A small outcrop of banded graywacke-type sediments exhibiting graded bedding was observed within the greenstones on the south shore of Kashabowie Lake, about thirteen chains west of the crescent-shaped island in the southeast bay (see Fig. 2). As far as could be ascertained, these sediments were within the greenstone series, but no contact was observable.

A quartzite of possible sedimentary origin has been reported within the Keewatin east of Burchell Lake.[19] The writer examined this quartzite and found that the exposures showed a complex of greenstone, quartzite, and sericite schist, which could not be separated from one another except by very detailed mapping. It was concluded that the quartzite showed evidence of being a replacement deposit, this being suggested particularly by its chalcedony-like nature. Moore concluded that it was a quartzite deposited on the Kee-

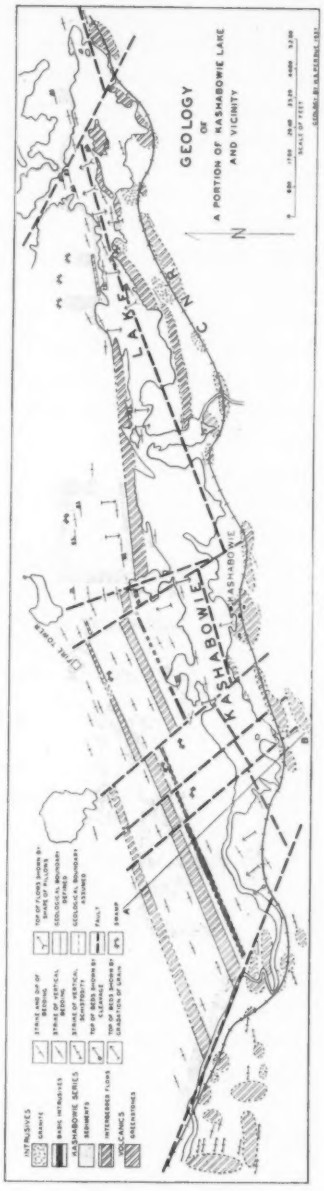

FIG. 2

[19] E. S. Moore, "Geology of Tip Top Mine," *Ontario Bureau Mines Rept. 20*, Part I (1911), pp. 209–13.

watin rocks and infolded. For greater detail the reader is referred to Moore's description.

The metamorphosed greenstones were not subdivided by the writer as had previously been done by Watson,[20] who attempted to divide the series in Moss township into acidic and basic types and mapped them as such. The writer collected suites of samples across the contacts as mapped and found no good basis for the separation. Watson has admitted that "the two types are so frequently intermingled that a decision is very difficult. The map simply indicates the dominant rock type."[21] Watson's descriptions of these Keewatin rocks and Tanton's[22] descriptions of what is believed to be the same series to the east are adequate for general purposes, and the writer cannot materially add to what is already known about the series.

Structural studies show that these Keewatin rocks are isoclinally folded. Their thickness was not determinable, but, even allowing for much repetition due to folding, the original thickness must have been considerable, for the belt has been stated to be about 14 miles wide.[23]

KASHABOWIE SERIES

Distribution.—The Kashabowie series occurs in an irregular wedge-shaped area within the district mapped. These sediments form a belt which is approximately half a mile in width at the eastern border and nearly 8 miles wide at the western border of the map area. The series is bounded on the north by a granite with which there is a gradational contact characterized by lit-par-lit injection gneisses and pegmatitic intrusions. The southern border is the contact with the greenstones from which the Kashabowie series is separated by a fault.

Lithology.—The Kashabowie sedimentary series is largely composed of graywacke-type rocks which are characteristically pale to medium gray in color, commonly weathering to a buff shade. They are mostly very thin bedded, the layers ranging from one thirty-second up to several inches in thickness. What are apparently wider bands are observed in places, but closer inspection usually discloses the smaller units within the larger. The rocks are medium to fine

[20] *Op. cit.*, p. 114.
[21] *Ibid.*
[22] *Op. cit.*, p. 60.
[23] *Ibid.*

grained and exhibit a sandy appearance on weathered surfaces. Alteration has brought about the development of micas which have grown parallel to the bedding planes, causing the rocks to have shiny cleavage surfaces and to be termed "mica schist." The micas are most prominently developed in the sediments in the broad contact zone near the granite and in xenoliths within the batholithic borders. Here the mica is of a darker variety and gives rise to dark-gray and black bands of coarse-grained gneissic material sometimes described as paragneiss. These more pronounced mica schists of the contact zone grade almost imperceptibly into the finer-grained, lighter-colored graywacke-type rocks farther removed from the contact zone.

Thin slaty bands of a dark-gray variety with pronounced slaty cleavage are not uncommon in the assemblage. Megascopically they appear to be a dark fine-grained phase of the typical graywacke, and on good exposures there are graded bedding relationships between the two types.

Chlorite schist beds were occasionally observed interbedded in the graywackes. Bands of this type were called "films" by McInnes,[24] who regarded them as remnants of unassimilated Keewatin. These bands are mostly but a few inches in width, 16 inches being the widest seen. The bands are fairly persistent and vary little in width except where they show pinch and swell phenomena due to dynamic metamorphism. They are regarded as chloritized tuff beds within the series.

On the rocky prominence on which the fire tower is located (Fig. 2), adjacent to the north contact of the northernmost greenstone bed, there is an exposure of fine-grained light-gray tufaceous-appearing rock which occurs in fine bands separated by chertlike layers. Within a zone 4–5 feet in width at this outcrop, there are angular fragments of dark-green basic schist, varying in size from an inch up to as much as 22 inches longest dimension. The fragments were variously oriented with respect to the bedding, and their schistosity was transverse to that of the enclosing material. These fragments are thought to be volcanic bombs interbedded in what is probably tufaceous material.

[24] *Op. cit.*, p. 42.

Further evidence of contemporaneous vulcanism is the presence of flow rocks of dark-green chloritic schist material interbedded with the sediments. These have been found to outcrop within the sedimentary series almost continuously for a distance of nearly 12 miles.

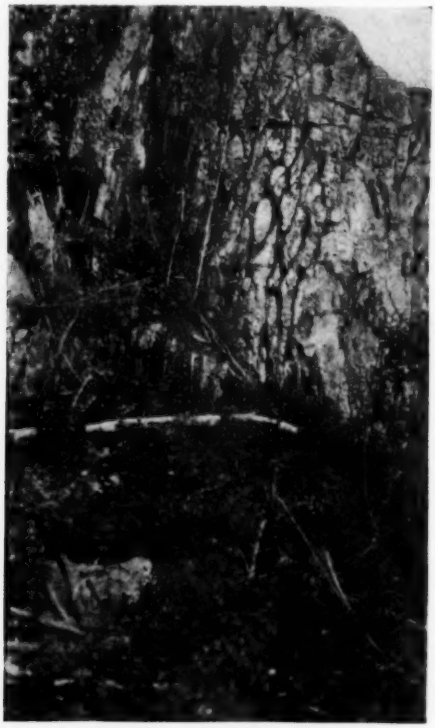

FIG. 3.—An exposure of pillow lavas interbedded with the sedimentary series northwest of Burchell Lake.

One of these bands in the eastern part of Ames township was over a mile from the sedimentary border. These flows were first observed northwest of Burchell Lake, where several outcrops exhibit unmistakable pillow lava structures (see Fig. 3). These pillow structures, unfortunately, were not found to give reliable top and bottom deter-

minations. The writer was, at first, inclined to regard the flows as infolded Keewatin, but evidence to prove their superposition within a syncline was lacking. Top and bottom determinations in the adjacent sediments also were doubtful. Weathering, producing discoloration and other surface changes, was found to have obscured graded bedding relationships. For such determinations the best outcrops are on lake shores, where they are subjected to wave wash, or where uprooting of trees or stripping operations have freshly exposed the bedding.

To the east in the area selected for detailed study the evidence indicated that these flows were interbedded. The broad band which outcrops on the north shore, northeast of Kashabowie village, has several well-exposed contacts with the sediments on its northern border. At these exposures freshly stripped outcrops show graded bedding, which indicates that the top is to the south or toward the greenstone band. The greenstone has a well-defined amygdule zone occurring within a few inches of the sharp conformable contact with the sediments. At places more remote from the contact, pillow lava structures were observable, which together with the unmistakable amygdule zone are proof of the effusive nature of this band of greenstone.

This same band may be traced eastward along the shore until it disappears beneath a prominent drift ridge. It reappears in the next bay to the east, outcropping on the shore just northeast of the small island shown on the map (Fig. 2). The greenstone at this outcrop is separated from the sediments on the south by a small depression. These sediments show graded bedding suggesting top to the south. This is verified by the well-exposed graded bedding on the eastern shore of the small island a few yards to the west. Here the top is clearly to the south (Fig. 4).

The use of graded bedding, i.e., the common occurrence of coarser material at the bottom of each layer grading into finer material above, as an infallible criterion for distinguishing top and bottom of layers has been questioned by Lawson.[25] More recently H. C.

[25] F. F. Grout, "Coutchiching Problem," *Bull. Geol. Soc. Amer.*, Vol. XXXVI (1925); discussion by Andrew C. Lawson, p. 363.

Cooke,[26] has cited evidence of anomalous grain relationships. Such are to be expected, but they are exceptional. In any event, it is now generally accepted by students of the pre-Cambrian that graded bedding in the finer sediments may be used to determine top of the beds when the studies show that this type of bedding is typical of the area and consistently gives determinations which are in accord with conclusions based upon other evidence.

FIG. 4.—The exposure of graded bedding adjacent to the greenstone flow as described in the text. Hammer pick points south. (Photo by F. J. Pettijohn.)

Graded bedding was found to be a reliable criterion in the Kashabowie area. This being so, it is safe to conclude that, since the adjacent steeply dipping sedimentary beds on both sides of the greenstone band have their tops to the south, the greenstone band is interlayered with the sediments. The sediments to the north are older and those to the south are younger than the greenstone flows which do not owe their present position to a synclinal structure such as would naturally be postulated if the sediments were all older than the greenstone schist band.

[26] "Anomalous Grain Relationship in the Caldwell Quartzites of Thedford District, Quebec," *Proc. and Trans. Roy. Soc. Canada*, Vol. XXVII, Sec. IV (3d ser., 1931), pp. 71–74.

Continuing along the north shore eastward from the island, all determinations of a reliable nature consistently indicate top of the sediments to the south. This verifies the other determinations and gives additional proof that the greenstone is interbedded with the sediments. This same flow has been traced westward from its outcrops on the north shore to where it is terminated by a cross fault. This band was not only located by means of transverse traverses but

FIG. 5.—A typical conformable contact between the darker interbedded greenstone and the lighter colored sediments. Hammer head marks contact.

was carefully examined by a longitudinal traverse throughout its length. Both the northern and the southern contacts with the sediments were observed many times and always showed conformable relations (see Fig. 5). Pillow lava structures which, though here unreliable for top-bottom determinations, were good enough to furnish proof of the flow origin of these rocks and were observed at various places throughout most of its length. The results of this longitudinal traverse verify the conclusion that this band constitutes a basic flow interbedded in the sediments. As such it may be used as a horizon marker.

The other occurrences of interbedded basic material were not traced with the same thoroughness as the band just described, but

sufficient traverses were made to delineate them as shown on the map. The more northerly of the bands in the key area is also regarded as effusive. The smaller southern unit is apparently composite in nature, for it displays coarse crystalline texture suggestive of a sill, and yet what appeared to be ellipsoidal flow structures were observed toward its western termination. Since a detailed examination of this band was not essential to this study, no effort was made to map it in detail.

Thickness of the sedimentary series.—The Kashabowie series is isoclinally folded and the details of the structures are too imperfectly known to permit an estimate of the total thickness. A section measured from the fire tower to the north lake shore would apparently give a minimum thickness of 4,000 feet.

Deposition of the Kashabowie sediments.—The outstanding feature of the Kashabowie series is the uniformity of the great bulk of the graywacke rocks. Even in the western portion of the area, where traverses crossed several miles of sedimentary outcrops, a monotonous succession was characteristic. Conglomerates were not observed in the series, nor was any cross-bedding seen. Gradation of grain size from coarse to fine within individual layers was, however, a common feature.

Lawson[27] considered the Coutchiching sediments to have been a basin deposit and the Seine series to be in part, at least, of flood-plain type. Bruce[28] postulated a huge delta of sufficient areal extent to include all the mica schists of northwestern Ontario. But no evidence of the delta type of bedding was observed by the writer. The problem is: How was this enormous bulk of fine Kashabowie sediment deposited under the quiet conditions necessary to produce thin, evenly bedded deposits of the graywacke type? E. B. Bailey[29] has discussed graded bedded sandstones and believes them to be relatively deep-water deposits. He further suggests that there seems to be a connection between graded bedding and geosynclinal depression. C. W. Tyrrell[30] regards the graded bedding type of graywackes

[27] *Op. cit.*, pp. 23 and 62. [28] *Op. cit.*

[29] "Sedimentation in Relation to Tectonics," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), pp. 1713–25.

[30] "Greenstones and Graywackes," *Bull. Comm. Geol. de Finlande 102* (1933), pp. 24–26.

as marine or geosynclinal and has emphasized their widespread association with greenstones.

The Kashabowie sediments are mainly of the sandy graded bedding type and probably were deposited in waters deep enough to prevent disturbance of the thin layers. Thus they may have been laid down in a geosynclinal basin.

Correlation of the Kashabowie sediments.—The fact that the Kashabowie sediments contain volcanic admixture may cause some to regard them as a phase of the Keewatin. Lawson[31] has included mica schists within the Keewatin in the type area. The additional fact that the top of the Kashabowie sediments is, in many places, toward the greenstone lends support to such conclusions. However, it will be shown that, where such relations exist, the contact is a fault. Structural relations which will be discussed later suggest that Keewatin lavas are older than the Kashabowie series.

At Kashabowie,[32] and to the east in Goldie township,[33] the sediments have been mapped previously as Coutchiching as a result of Tanton's investigations. Tanton, in accord with Lawson, regards the Coutchiching as free from volcanic admixture, for he states, "This is a mica-schist assemblage and it embraces no lavas where I have mapped it."[34] Therefore, since the Kashabowie sediments do contain volcanic admixture, they cannot be correlated as Coutchiching of pre-Keewatin age.

In Goldie township, where Tanton has mapped the Coutchiching, a conglomerate occurs along the border between the mica schists and the greenstones. According to the description it is part of a series which Tanton has provisionally considered as equivalent to the Windigokan. The series contains a basic conglomerate, arkose, graywacke or tuff, and an iron-bearing slaty formation. The whole series is about 1,600 feet in thickness and is said to be infolded in the Keewatin. The Kashabowie series is lithologically dissimilar, much thicker, and is not infolded in the Keewatin. However, the base of the Kashabowie series is not known; if it were exposed and found to include a basal conglomerate, it might be regarded as a later phase

[31] *Op. cit.*, p. 35.

[32] Kenora sheet, *loc. cit.* [33] Tanton, *op. cit.*

[34] "Stratigraphy of Lake Superior Region," *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), pp. 731–44.

of the Windigokan. Tanton has already mapped the Windigokan as distinct from the mica schists, and the writer accepts his judgment in the matter.

Tanton has suggested that the series provisionally regarded as Windigokan may be equivalent to the Steep Rock series[35] which he has classified with the Seine.[36] Merritt[37] has studied the Steep Rock series and failed to establish Tanton's correlation. More recently Tanton has classified a series in the Mine Centre area[38] containing conglomerate, quartzite, slate, greenstone, and altered sediments as Seine in age. The Kashabowie series, however, has little lithologic similarity to any of these conglomerate-bearing groups. Nor do they strongly resemble the finer clastics of the Seine series as described by Merritt.[39]

It seems, therefore, that the attempt to correlate this series must be carried farther afield—namely, to the Knife Lake slate area. Descriptions of the Knife Lake slates, as presented by Grout,[40] show many features which are common to the Kashabowie series. It is true that the Knife Lake slates have a basal conglomerate and coarse pebbly bands. But, as the conglomerate is patchy in occurrence and the pebbly bands are of minor importance, the absence of these phases in the Kashabowie series does not weigh seriously against correlation. In most respects they are similar. Both series are banded and have graded bedding of the sandy type, containing much graywacke material. Alteration to biotite schists by the granite intrusive is also a feature common to the two series. The broad contact zone characterized by injection gneisses and the biotite-schist inclusions in the granite of the Minnesota area are almost identical with the corresponding features so well developed in the Kashabowie series. In addition, both series occupy a similar position with respect

[35] "Eastern Part of Matawin Iron Range, etc.," *op. cit.*, p. 17c.

[36] "Recognition of the Coutchiching near Steep Rock Lake, Ontario," *Trans. Roy. Soc. Canada*, Vol. XX, Sec. IV (1926), p. 48.

[37] *Op. cit.*, p. 360.

[38] "Mine Centre Area," *Canada Dept. of Mines Geol. Surv.* (1936), Map 334A.

[39] *Op. cit.*, p. 347.

[40] "Contact Metamorphism of the Slates of Minnesota by Granite and by Gabbro Magmas," *Bull. Geol. Soc. Amer.*, Vol. XLIV (1933), pp. 989–1040.

to batholiths which may prove to be contiguous. Therefore, it seems to the writer that correlation with the Knife Lake slates appears more probable than with the Windigokan or Seine.

Grout believes that the mica schists of Minnesota and those across the batholith in the Rainy Lake region are continuous.[41] More detailed work may prove that the mica schists of the northern subprovince of the Lake Superior region are all of the same general age and are the time equivalents of the Knife Lake series.

GRANITES

The granitic intrusives and their accompanying pegmatitic injections occur as two types within the Kashabowie area. Those contacting the sedimentary series on the north are part of a huge batholithic mass, whereas the intrusives of granitic nature within the Keewatin are of the boss type. These latter masses were mapped and described by Watson.[42] Careful traversing by the writer showed that the mass north of Burchell Lake is connected with the intrusive southwest of the lake by a narrow neck extending along the west shore of the lake. Watson had mapped these as separate intrusions. The mass north of Burchell Lake was found to be less extensive than previously mapped. Part of the eastern border of the mass southeast of Burchell Lake was obscured by drift and not determined.

These bosslike intrusions show variations from granite to syenite, hornblende-biotite granite being the common type, but locally syenitic phases are evident. The rocks, in the main, display no unusual features, and for further description the reader is referred to Watson's treatment.[43]

The batholithic mass north of the sediments has gradational contact with that series. The contact zone is from 1 to 4 miles in width and is characterized by lit-par-lit granitic and pegmatitic injections into biotite schists. The location of a definite contact was very difficult. If the proportion of granite type rocks predominated, they were mapped as granite; whereas, if the biotite schists made up more than 50 per cent of the observed outcrops, they were included within the sedimentary borders.

[41] "Coutchiching Problem," *op. cit.*, p. 360.

[42] *Op. cit.* [43] *Ibid.*, pp. 116–19.

The present study was not carried beyond the contact zone because the main batholith lay to the north of the area mapped. This same batholithic mass extends to the east, and Tanton[44] has noted that it is a gray biotite granite.

Observations made within the contact zone suggest that the granites of the area present a good field for study. It was noted that all the granitic injections within the Keewatin greenstones were of a pink variety, whereas those in contact with the sediments were commonly gray to white. There appeared to be a change from gray to pink shades farther from the batholithic borders. One very unusual outcrop displayed both the gray and the pink granites with a gradational contact. There was no evidence of two periods of intrusion; no chill zone or change of grain size such as would be expected. Megascopically, the granites were the same except for color. A feature of this exposure was the fact that the gray granite contained biotite-schist inclusions while the pink variety was free from inclusions. Field notes do not show instances of inclusions within the borders of pink granite outcrops. Thus it is apparent that if these observations are typical a problem of assimilation or migmatization may be involved. The scope of the present study did not permit further investigation of this problem.

STRUCTURAL GEOLOGY

FOLDING

As will be evident from a study of the map (Fig. 2) the observed dips of the bedding and the schistosity show the beds to be isoclinally folded and slightly overturned in many places. The strikes of the Kashabowie sedimentary beds in the key area may be grouped into two sets. Those adjacent to and west of the fire tower average about N. 60°–70° E. and those east of the fire tower average N. 70°–80° E. This indicates a change of fold trend in the sediments just north of Kashabowie village.

South of the lake the observed strikes of bedding and schistosity within the greenstones do not display this change of trend, so apparent in the sediments. The strike of the greenstones averages N. 65° E., roughly parallel to the sedimentary trend west of the fire

[44] "Eastern Part of Matawin Iron Range, etc.," *op. cit.*, p. 18*c*.

tower, but at an angle to that to the east. This angular discordance between the two series is increasingly more apparent toward the eastern portion of the lake. It is also very marked $2\frac{1}{2}$ miles west of the village where the greenstones have strikes varying from N. 85° E. to N. 85° W., while the adjacent sediments strike about N. 60°–70° E.

Pillow shapes show the top of the greenstone series to be to the north, indicating the north limb of anticlinal fold in the greenstone facing the sediments to the north. Good exposures on the crescent-shaped island in the southeast bay of the lake exhibit pillow structures which show greatest concentration of amygdules within the north border of the pillows, a dominance of convex curvatures toward the north, and downward-facing pillow points with their apex to the south. All three generally accepted methods of determining top and bottom of flows from ellipsoidal structures are here applicable, and all indicate top to the north.

About thirteen chains west of this island a small patch of sediments on the south shore, apparently interbedded in the Keewatin, has good graded bedding which shows top to the north. Continuing westward the pillow lava zone may be traced discontinuously to beyond Kashabowie village. Evidence wherever deemed sufficiently reliable for safe determination consistently indicated that top lay to the north. Just south of Kashabowie station there are several exposures of pillow lavas where determinations may be made.

North across the lake the sedimentary series, with one exception, shows from observed determinations that top is to the south. Thus the north limb of a synclinal fold in the sediments is opposed to the north limb of the Keewatin anticlinal fold just described.

South of the river and west of the southwest bay of the lake, about fourteen chains west of milepost No. 82, sediments not previously mapped are exposed to the north of the railroad. These sediments have their top to the north. Therefore, a synclinal structure must here exist in the sedimentary series, and this is shown in the cross section (Fig. 6). The south limb of this syncline is not evident farther east because this fold has been truncated by a fault.

It is of significance that the width of the belt of sediments, as measured from the main interbedded flow to the greenstones on the south, varies considerably. One mile west of Kashabowie village the

width is at least 2,600 feet. Twenty chains northwest of the village the width has decreased to about 2,100 feet. About 2 miles farther east the belt has narrowed to only 600 feet. This can only be explained by regarding the contact between the two series to be at an angle to the bedding. The differences in the fold trends of the two series and the evident truncation of the sedimentary group, together with the additional important fact that the tops of the two series are often opposed adjacent to the contact, indicate a transgressive contact.

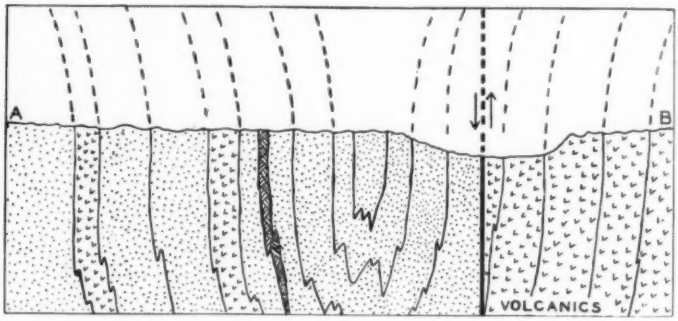

FIG. 6.—Cross section *A–B* (location shown on Fig. 2)

FAULTING

Boundary fault.—The unconformable relation existing between the Kashabowie sediments and the adjacent greenstones may be satisfactorily explained only on the basis of a fault contact. Such a fault has been shown on the map (Fig. 2). It is located for the most part in the lake bed and is nowhere observable. It is significant that studies to the west of the key area showed that similar conditions prevail there. Everywhere the sedimentary Keewatin contact occupies a depression. For a distance of 14 miles the writer has carefully traversed this contact and found it to occupy lakes, rivers, swamps, or drift-filled depressions. In places the two formations were exposed on opposite sides of a depression only a few yards in width. While the fact that the contact occupies a depression is not in itself proof of faulting, it becomes significant in the light of the discordant relations indicated by the studies in the key area.

The writer believes that this fault is very much longer than the 14 miles thus far recognized. Throughout the length studied, evidence of dip of the schistosity indicates that the fault plane in most places is essentially vertical.

Cross faults.—A large cross fault which offsets the boundary fault is located in the western portion of the key area. The amount of strike slip is over a mile as estimated from the displacement of the Keewatin sedimentary contact (see Fig. 1). The offset indicates a relative movement of the southern side to the northwest. In the key area this fault has a very prominent scarp on its northern side, especially along that portion following the river. Where the fault continues eastward in a straight line it forms a depression with a less pronounced northern scarp until it crosses the stream and is lost beneath the extensive moraine deposits in that portion of the area.

This fault is clearly younger than the greenstones and the sediments and the contact fault, but its age with respect to the granite was not determined. The gradational nature of the granite sedimentary contact rendered evidence of displacement of that boundary difficult to recognize.

It was noted by McInnes[45] that a fault which was in evidence at Baril Bay to the northwest seemed to agree in strike and displacement with one on Greenwater Lake to the southeast of the area studied by the writer. This fault would then be some 20–30 miles in length and should cross the writer's field of study about where the cross fault has been mapped. Merritt has since visited the Baril Bay area and has named the fault the "Baril Bay Fault."[46] He has estimated the displacement to be more than a mile. The direction of offset and the displacement agree with those of the fault described by the writer.

Minor cross faults.—Roughly paralleling the major cross fault are five smaller cross faults mapped in the key area. In each the direction of movement coincides with that of the major cross fault, i.e., the west side moved northward relative to the east side. A sixth fault is postulated in the eastern part of the key area to account for the displacement of the sedimentary greenstone contact so evident there. The five known and the one assumed fault have a total mini-

[45] *Op. cit.*, p. 32. [46] *Op. cit.*, p. 371.

mum strike slip of 1,100 feet. These, together with the major cross fault, would give a total slip of about 9,000 feet. The minor cross faults are not definitely known to displace the Keewatin, but there is every reason to think that they do unless the boundary fault has a very irregular strike where it crosses the key area.

These minor cross faults are typical of more than the key area, for similar ones were mapped northwest of Burchell Lake. There the tracing of interbedded flows in the sediments showed the existence of seven cross faults in a mile. The movement was in the same relative direction as along those of the key area.

In addition to the faults of sufficient magnitude to show on the map, there are innumerable smaller cross faults evidenced on outcrops throughout the entire sedimentary belt. These smaller faults have strikes which average 30°–40° east of south. Displacement is like that observed on the other cross faults, the west side being displaced northward a few inches or feet with respect to the east side.

INTERPRETATION OF FAULT STRUCTURES

It is apparent that the cross faults are all related, for their displacements are all in the same relative direction and their strikes roughly parallel, though in the key area there is some suggestion of a divergence in strike. This divergent pattern becomes more pronounced if the faults of the key area are grouped with those observed northwest of Burchell Lake, where the strike of the fault planes is nearly east-west. These cross faults were apparently due to tension such as would develop from the shove of an arcuate Keewatin block against the sedimentary unit. The diverging trend of cross faults recalls the familiar pattern of tear-faulting strikingly displayed in the Jura Mountains[47] where outward thrusting from the Alpine arc has produced numerous diverging transverse flaws. In the Savant Lake region of Ontario, Rittenhouse[48] found cross faults displacing a major strike fault in a manner very similar to those of the Kashabowie area.

The boundary fault which separates the Keewatin from the sedi-

[47] Albert Heim, *Geologie der Schweiz;* see illustration in *Jour. Geol.*, Vol. XXXVI (1928), p. 537.

[48] Gordon Rittenhouse, "Geology of a Portion of Savant Lake Area, Ontario," *Jour. Geol.*, Vol. XLIV (1936), pp. 451–78.

mentary series does not show any evidence of horizontal movement. No drag in the bedding adjacent to the fault was observed, but the fact that the fault plane truncates the folds is suggestive of at least some horizontal movement. So far as could be ascertained, the fault plane is essentially vertical. Analysis of structures involved points to upthrust of the south side. The cross section (Fig. 6) shows the north limb of a Keewatin anticline apparently thrust upward with respect to the sedimentary syncline on the other side of the fault plane. This is suggestive of a high-angle break-thrust type of fault. To suppose the syncline thrust upward with respect to the opposing anticlinal limb is not in accordance with the accepted ideas of thrusting. To give further support to the suggestion that the south block has been upthrust are the crude mullion structures exposed on the north shore of the southeast bay of Kashabowie Lake. Here the rocks show slickensided and sheared surfaces which dip to the southeast. Furthermore, the majority of recorded dips are to the north, and, although the departure from the vertical is small, it does favor upthrust of the south side. The evidence just cited to show upthrust of the south side is not conclusive, and it might be taken to indicate a normal fault dipping to the southeast. The normal-fault interpretation is not favored because it involves tension forces which do not harmonize with the forces which produced the cross faults.

This boundary fault roughly parallels the Sapawe Lake fault described by J. E. Hawley,[49] and the direction of inferred movement is almost the same, though Gill[50] and Merritt[51] have questioned Hawley's interpretation of the fault movement. In general, the Kashabowie type of faulting is not very different from that encountered in various other areas of the pre-Cambrian shield.

In the Kashabowie area the active displacements which produced the boundary fault and the cross faults offsetting it are regarded as having come from the south. While there may have been two periods of faulting, this is not necessarily required. It is suggested that pressures from the south could have thrust the Keewatin block

[49] "'Seine' or 'Coutchiching,'" *Jour. Geol.*, Vol. XXXVIII (1930), pp. 521–47.

[50] J. E. Gill and J. E. Hawley, "'Seine' or 'Coutchiching'" (discussion), *Jour. Geol.*, Vol. XXXIX (1931), pp. 655–69.

[51] *Op. cit.*, p. 364.

against the sediments to the north which are in a slightly arcuate belt convex on the north. The result of this thrust may have been the creation of longitudinal tension in the curving sedimentary block. This tension would be greater with a steep fault plane such as probably existed. The sedimentary block, in the Kashabowie area, as it was bent around the blunt nose of the northward-thrusting Keewatin, fractured under this tension, producing the cross faults so common to the area. These cross faults probably extended into the Keewatin block, since that advancing unit would shove into the gaps along the sedimentary border developing as a result of the relief when the tension breaks occurred. Thus one period deformation may account both for the boundary fault and for the cross faults.

BEARING OF STRUCTURE ON THE AGE RELATIONS OF THE KEEWATIN AND THE KASHABOWIE SERIES

The structures described in the Kashabowie area show conclusively that the Kashabowie sediments are not overlain conformably by the Keewatin series. Since the contact has been shown to be a faulted one, the relative ages of these two series is not determinable at this place. On the assumption that the upthrust side is eroded more than the downthrow side, it is natural to suppose that the rocks exposed on the upthrow side are the older. The writer questions the validity of such an assumption for the isoclinally folded rocks exposed on either side of the high-angle boundary fault in the Kashabowie area. The depth to which the nearly vertical folded rocks of both the Keewatin and Kashabowie series extended is not known, but was probably many thousands of feet, since both series were doubtless of considerable thickness prior to isoclinal folding which would increase the relative thickness. Even assuming great vertical displacement and considerable erosion of the upthrust side to account for the exposure of deeply buried rocks, there is no necessity for the conclusion that the rocks thus exposed are older than those which have been eroded. They may be the continuation of the same beds.

Little is known concerning the basement relations of isoclinally folded rocks. Cooke[52] has estimated a removal of from 14,000 to

[52] "Kenogami, Round and Larder Lake Areas, Timiskaming District, Ontario," *Canada Dept. of Mines Geol. Surv. Mem. 131* (1931).

31,000 feet of steeply folded rocks, and yet the beds now exposed still dip isoclinally and extend to unknown depths. In the Kashabowie area the depth to which the isoclinally folded sediments and greenstones extended, the amount of upthrust, and the thickness removed by erosion are not known and are at present incalculable. Therefore, it is doubtful if any fair conclusions as to the relative age of the two series can be drawn from the inferred direction of thrust on the boundary fault. There is, however, some reason to conclude that the older, stronger unit would be the upthrust block, but even this criterion would have to be applied with caution.

It is to be expected that an area which has probably undergone two periods of orogeny and two erosive intervals should have a complex structure which can only be unraveled with difficulty. Chamberlin[53] has presented a thought-provoking summary of the orogenic history of the southern Canadian Shield. Upon the basis of his general synthesis the Kashabowie sediments would be expected to be of post-Laurentian age and equivalent to the Knife Lake slates of similar genesis. This is also in accord with the structural relations suggested by Pettijohn,[54] who has postulated some of the pre-Cambrian basins of deposition within the northern subprovince of the Lake Superior region. Pettijohn has outlined a southern basin, the northern border of which extends from the Rainy Lake area eastward through Shoal Lake area, Steep Rock Lake district, Sapawe Lake area, and probably extends to the Block Creek area. The southern border extends northwest from the Vermilion district of Minnesota to the Matawin iron range area in Ontario. Along the northern border of this postulated basin conglomerates have been reported[55] at Rat Root Bay, Neil Point, Cliff Lake, Shoal Lake, Pike Lake, Perch Lake, Jackfish Lake, Atikokan River, and Block Creek. These conglomerates lie between the mica schists to the south and the adjacent greenstones on the north. Along the southern border similar features seem to be indicated, though the mapping in this section has not been so complete. Conglomerates are known to occur in the Vermilion district at the contact of the mica schists and the greenstones to the south. What may be similar conglomerates have

[53] *Op. cit.*

[54] "Early Pre-Cambrian Geology, etc.," *op. cit.*, p. 156.

[55] Merritt, *op. cit.*

been mapped to the northeast in Goldie township, where they also occur between the mica schists and the greenstones to the south. Within this roughly elliptical mica-schist belt is a granite intrusion.

The general picture is that of a granitic mass bordered by mica schists, which are in turn bordered by greenstones with conglomerates between the two series at many places. The granite is considered to be Algoman in age. The mica schists and the greenstones of the northern and southern borders of this postulated basin are lithologically similar. Faulted contact between the greenstones and the sediments has been identified on the northern border in the Sapawe Lake area.[56] Roughly paralleling this fault is the boundary fault on the southern border at Kashabowie—a fault which may prove to be much more extensive than at present mapped.

The relations around this postulated basin of deposition are very suggestive. One readily visualizes the highlands bordering the area and the deposition of conglomerates at the base while the finer sediments were laid down in deeper waters. That the conglomerates are not more extensive in the relatively few areas studied around the borders of this basin may be due to faulting, erosion, original discontinuous deposition, and to concealment beneath drift-covered areas. Detailed work in the many areas yet to be studied will doubtless further our understanding of the problem.

The attempt to correlate the various mica schists on the basis of the location of the sites of deposition seems at the present stage of investigation more promising than attempts to correlate isolated areas of these sediments with greenstones which may be of differing ages. In some areas two periods of vulcanism have been reported in the "Keewatin."[57] The prevailing near-vertical bedding of the mica schists and the greenstones, coupled with fault relations, further complicates age determinations.

The writer has every reason to believe that further work will extend the belt of Kashabowie sediments much farther to the southwest. The trend is definitely toward the Knife Lake slate areas, and the results of further work may establish connection. Until more work is done, one may conclude that the lithologic similarities and

[56] Hawley, *op. cit.*

[57] Pettijohn, "Geology of East Bay, etc.," *op. cit.;* Rittenhouse, *op. cit.*

the broader structural relations are very suggestive of a common age for the mica schists of the Kashabowie area and those of the Vermilion district; they may be part of one great basin deposit of Knife Lake age.

ACKNOWLEDGMENTS.—The problems of the Canadian Shield and the methods of study first claimed the attention of the writer while attending lectures on that subject given by R. T. Chamberlin. For interest and aid in interpreting structural features of the selected area, the writer owes a considerable debt to Professor Chamberlin.

Introduction to and instruction in actual field work in northwestern Ontario was generously and ably given by F. J. Pettijohn, whose suggestion led to the selection of this particular problem and area for study. The writer is also indebted to him for later checking the determinations in the field and invaluable aid in the construction of maps and preparation of the manuscript.

To the director, Bureau of Economic Geology, Department of Mines, Canada, thanks are due for the opportunity to map and report on the area while acting as student assistant in 1936. To T. L. Tanton, head of the survey party, who introduced the writer to the problems of the area and rendered every possible assistance during the study, sincere thanks are due. It is with keen regret to the writer that independent and more detailed studies made in 1937 disclosed new field facts which do not harmonize with the conclusions reached by Tanton. To Messrs. K. Scott, D. P. Best, and J. A. Enstone, field assistants in 1936, and D. R. MacKay and G. Thorman, assistants in 1937, grateful acknowledgment of their excellent services is here tendered. Thanks are also due to many residents of the area for the countless ways in which they facilitated the work.

THE TENSLEEP FAULT, JOHNSON AND WASHAKIE COUNTIES, WYOMING

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ABSTRACT

The Tensleep fault, with downthrow on the south, is a major transcurrent fracture separating the central and the southern segments of the Bighorn Mountains, which have, respectively, an overthrust eastern front and gently sloping western flank and a steeply dipping or overthrust western front and gently dipping eastern limb. The abrupt replacement of this fault by the Horn fault near the eastern mountain front indicates that the Tensleep fault and the Bighorn Range were of contemporary origin. That the fault movement had an early, tensional phase, followed by one of compression is indicated by the belt of strongly dipping beds dragged up on the downthrow side (south); the local reversal of down-dragged beds on the upthrow side (north) resulting in drag away from the fault plane on that side; the local rotation of the fault plane causing it to dip to the north; and the extremely sheared condition of beds near the fault.

INTRODUCTION

The Bighorn Mountains consist of a large, compound uplift that arose above the nearly flat-lying strata of the surrounding plains during the Laramide revolution. As studies have indicated,[1] this uplift is not a simple, asymmetrical "anticline" but rather is an elongate composite uplift consisting of individual horstlike or "ramplike" crustal blocks with the mantling sediments draped over the basement crystalline rocks. Future detailed work will indicate the exact number and relative position of these individual crustal blocks, but for the purpose of this report they are grouped into three major segments: northern, central, and southern (Fig. 1). In the northern segment of the Bighorns, thrusting was toward the west,[2] and the steep sides of the associated sharp monoclinal folds face the west. The strata on the eastern side of the range dip gently eastward. In the second, or central, segment of the Bighorn Mountains a sharp, oversteepened, and locally thrust monoclinal fold occurs

[1] N. H. Darton, "Geology of the Bighorn Mountains," *U.S. Geol. Surv. Prof. Paper 51* (1906); W. H. Bucher, R. T. Chamberlin, and W. T. Thom, Jr., "Results of Structural Research Work in Beartooth-Bighorn Region, Montana and Wyoming," *Bull. Amer. Assoc. Petr. Geol.*, Vol. XVII (1933).

[2] C. W. Wilson, Jr., "A Study of the Jointing in the Five Springs Creek Area, East of Kane, Wyoming," *Jour. Geol.*, Vol. XLII (1934).

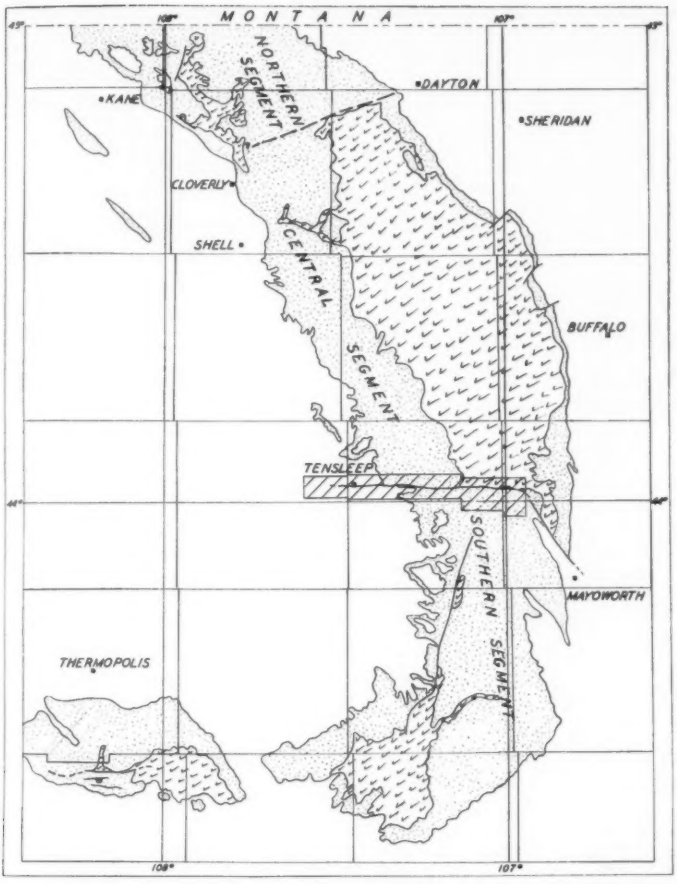

FIG. 1.—Geologic index map of Bighorn Mountains, Wyoming, showing three major segments of these mountains and relationship of Tensleep fault to the central and southern segments. The area mapped for this report is indicated by diagonal lines, outcrop of pre-Cambrian rocks by checks, and outcrop of Paleozoic rocks by stipples. The surrounding white area is covered by Mesozoic and Cenozoic sediments. Modified after state geologic map of Wyoming.

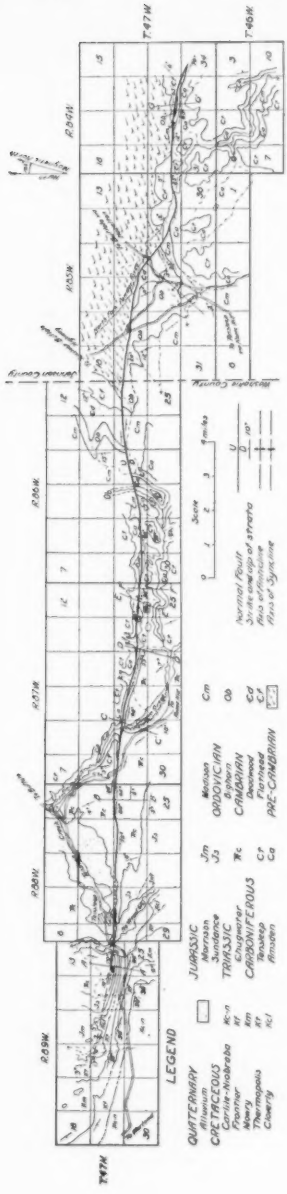

FIG. 2.—Areal geologic map of the Tensleep fault and vicinity, Johnson and Washakie counties, Wyoming

along the eastern mountain front, and the western slope of the mountains is characterized by gentle westward dips. The southern segment includes that part of the mountains south of the Tensleep fault (Fig. 1), and within this unit conditions are similar to those in the northern segment, for oversteepening and westward thrusting of strata occur along the western flank of the mountains opposed by a gentle eastern dip along the eastern flank.

Under these circumstances it seemed probable that a detailed study of stratigraphic and structural relationships along the Tensleep fault zone might afford definite evidence of the deformational mechanics and forces by which the Bighorn Range had been produced, and this study was consequently undertaken by the writer, as a part of the Yellowstone–Bighorn Research Association's structural program. During the summer of 1936 the Tensleep fault was mapped for a distance of 28 miles, and the associated (but unbroken) monocline, continuing the western end of the fault, was traced for 5 miles farther west, making a total distance of 33 miles (Fig. 2). The mapped area averaged 3 miles in width, but varied between 1 and 5 miles. The mapping was done with alidade and plane table at a scale of 2 inches to a mile.

This fault had originally been mapped and described by Darton[3] and had also been studied in reconnaissance fashion by Bucher, Chamberlin, and Thom.[4]

STRATIGRAPHY

The rocks exposed along the length of the Tensleep fault and associated monocline range in age from pre-Cambrian to the Niobrara-Carlile shales of the Cretaceous system. The various formations are described briefly in the following composite section.

TABLE 1

	Thickness in Feet
Cretaceous system:	
Niobrara-Carlile shale	
Black shale	Thickness not taken
Frontier formation (1½ miles west of Tensleep)	
Yellow to buff sandstone, locally very thin	15
Dark-gray and black shale, occasional sandstone layer	120
Local conglomerate	8
Dark-gray and black shale, occasionally sandy	50
Yellow and light-brown sandstone	12
Gray sandstone and shale, containing many bands of bentonite, and weathering into badlands characterized by white, gray, and black streaks	60
Alternating black and gray shale with bentonite beds	80
Light yellow to buff sandstone	10
Black and dark-gray shale	80
Gray, thinly bedded sandstone, containing many specks of white and black minerals, and grading down into the underlying gray shale of the Mowry	15
Total thickness	450
Mowry shale (1¼ miles west of Tensleep)	
Gray siliceous shale and some black shale	90
Sandstone	5
Gray siliceous shale	117
Hard siliceous sandstone	8
Gray siliceous shale with many fish scales	110
Total thickness	330

[3] N. H. Darton, *U.S. Geol. Surv. Atlas, Cloud Peak–Fort McKinney Folio No. 142* (1906); "Geology of the Bighorn Mountains," *op. cit.*

[4] *Op. cit.*

TABLE 1—*Continued*

	Thickness in Feet
Thermopolis shale (1 mile west of Tensleep)	
Black shale with many bands of bentonite	285
Irregularly bedded, medium-grained, light-buff to white sandstone	15
Black shale as above	235
Total thickness	535
Cloverly formation (1 mile west of Tensleep)	
Graybull member	
Thinly bedded, fine- to medium-grained, rusty-brown sandstone, interbedded with thin layers of black shale. About 5 feet of this member is locally massive. Ripple marks abundant	25
Varicolored shales (several miles west of Tensleep this member is 200 feet thick)	60
Pryor member	
Medium-grained, massively bedded, cross-bedded sandstone; usually white, sometimes buff; and locally containing pebbles of black chert	30
Total thickness	115
Jurassic system:	
Morrison formation (1 mile west of Tensleep)	
Maroon shale; brown, gray, and green shale with thin layers of sandstone; and black shale	185
Sundance formation (1 mile west of Tensleep)	
Green shale	100
Light-olive-green sandstone	20
Olive-green shale and occasional layer of limestone, sandstone, and sandy limestone	258
Hard gray limestone	4
Total thickness	382
Triassic system:	
Chugwater formation	
Red shale and red sandstone with occasional bands of gypsum and white limestone which commonly occurs in upper and lower parts of formation. Thin, purplish conglomerate occurs at base. Complete thickness not exposed in continuous section, but estimates average	800
Pennsylvanian system:	
Tensleep sandstone (6 miles east of Tensleep)	
White to yellow, medium-grained, cross-bedded sandstone	130
Sandstone as above, but with occasional break of red shale and other shaly beds	70
Total thickness	200

TABLE 1—*Continued*

	Thickness in Feet
Pennsylvanian and Mississippian systems:	
Amsden formation (6 miles east of Tensleep)	
Interbedded red shale, red sandstone, tan siliceous limestone with much red and yellow chert, and sandstone as in the Tensleep. Top 40 feet chiefly cherty limestone	100
Bright red shale	40
Medium-grained, poorly cemented, white sandstone that is massively bedded and extensively cross-bedded on a large scale. Surface often stained buff or red	72
Hard, fine-grained, siliceous limestone which is tan and buff cream in color	45
Total thickness	257
Mississippian system:	
Madison limestone	
Massively bedded gray limestone. Reported by Darton* to be 750 feet in thickness along the west flank of the Bighorn Range. Along the crest of the mountains the formation is no thicker than 500 feet	750
Ordovician system:	
Bighorn limestone	
Massively bedded, mottled dolomitic limestone, reported by Darton† to be about 300 feet in thickness	300
Cambrian system:	
Deadwood formation	
Dark-greenish shales with layers of limestone and sandstones. Near the top is a concentration of limestone and flat-pebble conglomerate	900
Flathead sandstone (?)	
Basal sandstone that is coarse grained and brownish red	50
Pre-Cambrian granite and basic inclusions.	

* N. H. Darton, *U.S. Geol. Surv. Atlas, Cloud Peak–Fort McKinney Folio No. 142* (1906), p. 5.
† *Ibid.*, p. 4.

STRUCTURE

The general structural pattern of the Bighorn Mountains suggests that a system or systems of pre-existing structural lines in the rocks of the basement complex influenced the yielding to the stresses of the Laramide revolution. It is furthermore suggested that, even though the crustal blocks, delimited by these pre-existing structural lines, were uplifted as a composite unit, each block nevertheless moved separately, being tilted in a different direction and being crowded against the adjoining blocks along the separating fractures.

The tilting of these blocks resulted in the development of sharp, monoclinal flexures or thrust faults along the uplifted edges of "trapdoors" as the mantling sediments were draped over the basement rocks. As compressive stresses became more intense, the uplifted edges of these tilted "ramplike" blocks were crowded over adjoining lower parts of adjacent blocks and locally pushed out, or thrust, over the nearly flat-lying strata of the surrounding plains.

The Tensleep fault thus obviously occupies a critical position in relation to the large-scale tectonic pattern of the Bighorn Mountains and is a major transcurrent fracture, separating the central and southern segments of the Bighorn Range, which have, respectively, an overthrust eastern front and gently dipping western flank and a steeply dipping or overthrust western front and gently dipping eastern limb.

This fault, whose downthrow is on the south, strikes approximately east-west throughout its extent and, at the western end, passes into a monoclinal flexure which pitches westward into the Bighorn basin.

At the western end of the mapped area the pre-Cambrian surface is estimated to be about 100 feet below sea-level. Six miles east of this locality, and in the vicinity of the town of Tensleep, the elevation of the pre-Cambrian is estimated to be 1,620 feet on the north side of the fault and 1,220 feet south of the fault. This would indicate 400 feet of displacement. On the crest of the anticlinal axis in Sec. 22, T. 47 N., R. 85 W., the top of the pre-Cambrian north of the fault is estimated to have been 9,200 feet above sea-level, before being lowered by erosion; whereas south of the fault the elevation of the pre-Cambrian is estimated at 7,850 feet, giving a throw of 1,350 feet. Within this distance of 23 miles the westward dip on the northern side of the fault averages 3.6°.

STRUCTURAL FEATURES OF THE TENSLEEP FAULT

The local structural details of the fault are described by townships from west to east, as follows:

T. 47 N., R. 89 W.—In Sec. 24 of this township the rupture of the Tensleep monocline first causes the Tensleep fault to be visible at the surface. Visible displacement on the fault here seems, how-

ever, to be limited to members of the Chugwater, as the top of that formation is apparently unbroken. The monoclinal fold that forms the western continuation of the fault causes the strongly dipping south limb to flatten out into the normal dip and strike of the eastern flank of the Bighorn structural basin. Dips in a stratum change abruptly from 50° to 3° in crossing the axis of the monocline from south to north, and its strike changes from N. 75° W. to N. 20° W. This change decreases toward the west and hence becomes

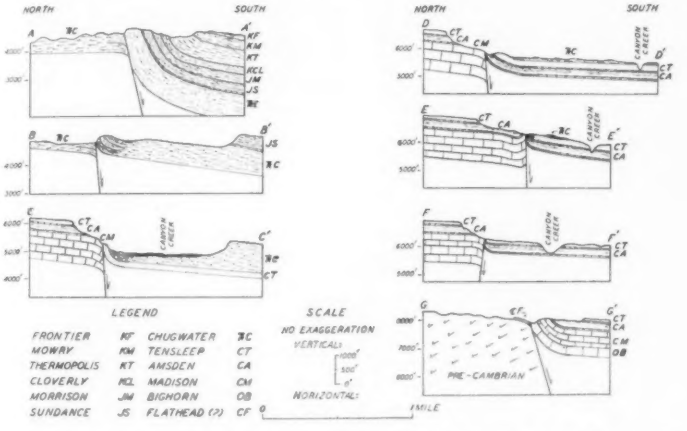

FIG. 3.—Structure cross sections across the Tensleep fault. The locations of these lines of section are indicated in Fig. 2.

progressively less in younger formations from the Sundance up to the Niobrara-Carlile shales.

In the western part of the township the fold is fairly well pronounced, and south dips of 20°–35° occur on the south limb. In the eastern half of the township dips on the downthrow side of the fault (and associated monoclinal fold) are to the south and average 50° for a distance of three-quarters of a mile from the fault plane (Sec. *A–A'*, Fig. 3). Close to the fault, dips are as high as 80°. Consistently high-angle drag three-quarters of a mile away from the outcrop of the fault plane is believed to be too great for drag associated with a simple normal fault resulting from tension. Rather,

it suggests an initial drag to the south, possibly not so steep as 50° and certainly not in so wide a belt as three-quarters of a mile, which was later exaggerated by northward crowding of the southern segment against, and possibly to some degree "under," the central crustal segment of the Bighorn Mountains.

Although the drag is everywhere up (south dip away from the fault) on the south side of the fault, it reverses on the north side, being 10° north (away from the fault) in the western part of Sec. 24, and several degrees south (into the fault) in the center of Sec. 24 (Sec. *A*–*A*′, Fig. 3). The writer is not acquainted with any case of drag associated with an originally deep-seated normal fault over which the sedimentary mantle was first draped and later broken in which the drag is away from the fault on both sides unless there have been compressive stresses active subsequent to the first movement.

T. 47 N., R. 88 W.—The fault is limited to the Chugwater formation. North of the fault there is drag of 20° toward the fault (south dip) which is restricted to the vicinity of the fault plane. At some distance north of the fault the regional strike of N. 25° W. and average west dip of 5° occur. South of the fault the drag dips to the south but is limited to within a few hundred yards of the fault plane, flattening out to an average of 5° (Sec. *B*–*B*′, Fig. 3).

T. 47 N., R. 87 W.—The Chugwater, Tensleep, Amsden, and Madison formations occur along the north side of the fault opposed to the Chugwater, Tensleep, and Amsden formations on the south. The throw of the fault averages close to 500 feet as the top of the Tensleep sandstone has been dropped on the south to about the level of the top of the Madison limestone. The shift of the two crustal blocks is greater than 500 feet, as an average drag of 55° occurs along the downthrow side and a drag of 20° along the north side. Sections *C*–*C*′, *D*–*D*′, and *F*–*F*′, Figure 3, illustrate the usual dips associated with the fault in this township.

Along a creek in Sec. 24 there is a very significant variation in the drag (Sec. *E*–*E*′, Fig. 3). South of the fault at this locality the drag, which is to the south as normally expected, is 30° for a short distance before flattening to 5°. The beds near the fault plane are cut by several vertical shear planes. Near the fault on the north side there

is a 30° dip to the north, which direction is distinctly out of harmony with development by normal faulting alone. As the ravine in which the drag was studied is followed northward upstream the drag reverses direction and dips 15° to the south, the direction commonly characteristic of this side of the fault, before exhibiting the usual 5°–12° dip to the west-southwest. The writer interprets this as indicating original orthodox drag associated with a normal fault (to the south on both sides of the fault) subsequently being subjected to compressive stresses that reversed the direction of dip near the north side of the fault from the original 15° to the south to 30° to the north.

In the eastern part of Sec. 24 the dip of the fault plane was determined in a deep ravine. Here the fault dips north about 85° (Sec. *F–F′*, Fig. 3), implying rotation of a fault plane that originally had dipped to the south. South of the fault at this locality the pre-Cambrian basement rocks are about 900 feet lower than north of the fault. As these lower competent rocks carried much of the brunt of transmitting compressive stresses during the Laramide revolution, the rotation of the fault plane from a high-angle fault dipping south to a high-angle fault dipping north could easily have resulted from the southern crustal segment of the Bighorn Mountains crowding "under" the central segment.

One of the best locations from which to view the fault is provided by the road in the NE. ¼, Sec. 29, the white palisades of very steeply dipping Tensleep sandstone near there being in marked contrast with the relatively flat-lying Amsden and Madison north of the fault (Fig. 4). An interesting contrast of color may be seen in the north-central part of Sec. 20, where the brick-red Chugwater formation is in contact with the maroon-colored shales of the middle part of the Amsden formation.

T. 47 N., R. 86 W.—Beds ranging from the Amsden formation to the pre-Cambrian occur on the north side of the fault; whereas, south of the fault beds range from the Tensleep sandstone to the Bighorn limestone. Exposures of drag on the north side of the fault are rare, but on the south side several exposures show a south drag of from 20° to 60°.

In Sec. 21 where Canyon Creek crosses the fault Madison lime-

stone forms the floor and lower walls of the canyon south of the fault. North of the fault the Madison is much higher and covers wide areas on both sides of the canyon in addition to the canyon walls. Bighorn limestone is believed to form the floor of the canyon on this side of the fault. In Sec. 24 the base of the Madison limestone has been dropped down to the top of the Flathead sandstone (?), a throw of 1,100 feet.

FIG. 4.—View on Canyon Creek in Secs. 19 and 20, T. 47 N., R. 87 W., showing steeply dipping Tensleep sandstone dragged up on the downthrow side of the Tensleep fault against relatively flat-lying Madison and Amsden formations. The foreground is floored with the Chugwater formation. Reproduced through the courtesy of N. H. Darton, U.S. Geological Survey.

T. 47 N., R. 85 W.—Pre-Cambrian rocks occur along the northern side of the fault in this township with the exception of Secs. 25 and 26, where the Flathead sandstone (?) is preserved resting on the pre-Cambrian granite. Near the fault the south dip of this sandstone steepens. The "axis" of the Bighorn uplift crosses the fault in Sec. 22. South of the fault the axis brings the Deadwood formation up to the surface with flanking outcrops of Bighorn and Madison limestone dipping southwest and southeast. At the base of the Bighorn limestone the dips to the southwest average 8°, while those

to the southeast average 35°. Near the anticlinal axis in Sec. 22 the throw is estimated to be about 1,350 feet.

In this township the writer's interpretation of the fault differs from that of Darton,[5] as the latter writer showed the Tensleep fault ending near the center of Sec. 20 and a separate fault starting in Section 33, curving it northeastward through Secs. 27 and 26 and then eastward toward the Horn. The present writer believes that the Tensleep fault continues eastward from Sec. 20 to the Horn, and that the curving fault recognized by Darton through Secs. 27 and 26 is the steeply dipping, and possibly locally sheared, flank of the anticlinal axis that crosses the major fault in Sec. 22. On this limb all the formations that should occur are believed to be present but thinned to varying degrees by stretching and shearing.

Five and a half miles north of the southern line of Sec. 22 the pre-Cambrian of the southern Hazleton Peak is 10,307 feet in elevation in contrast with pre-Cambrian rocks at 8,100 feet in Sec. 22. The general elevation of the peaks cut from pre-Cambrian rocks along the crest of the Bighorn Mountains from Hazleton Peaks to Cloud Peak suggests a low angle of pitch to the south for the Bighorn uplift. For this reason it is believed that the pre-Cambrian now exposed at the surface on the north side of the fault in Sec. 22 is much lower than the original top of the pre-Cambrian at this location.

T. 47 N., R. 84 W.—The mapped area extends eastward to the eastern line of Secs. 28 and 33, T. 47 N., R. 84 W. and Secs. 4 and 9, T. 46 N., R. 84 W. North of the fault pre-Cambrian and Cambrian rocks occur. The Flathead sandstone (?) dips southward about 5°, except near the fault where this dip is abruptly increased to 65°. South of the fault in Sec. 30 and in the western half of Sec. 29, the Amsden formation occurs along the fault and dips 12° or more to the south. Here the top of the Amsden is faulted down to about the same elevation as the top of the pre-Cambrian, a stratigraphic throw of approximately 1,900 feet. In Sec. 28 and in the eastern half of Sec. 29 a narrow strip of the Madison and Bighorn limestones occurs along the fault and dips southward about 60°. This

[5] "Geology of the Bighorn Mountain," *op. cit.*

dip flattens within a short distance to the south. This limestone is sheared extensively, and apparently both formations have been thinned as a result of shearing. The concentration of shearing along the fault plane here, as well as at many other localities, implies the action of compressive stresses.

Demorest[6] reports that the Tensleep fault continues southeastward through Sec. 34 and into Sec. 35, where it is replaced by the Horn fault, so named by Demorest because it forms the western boundary of the Horn, a prominent topographic and structural feature of the eastern front of the mountains. This fault has a northwest-southeast strike.

SUMMARY AND CONCLUSIONS

The Tensleep fault, near the eastern mountain front, apparently intersects the Horn fault, which is an integral part of the eastern structural front. The relationships of these faults indicate contemporary origin of the eastern structural front of the Bighorn Mountains and of the Tensleep fault. Corollary to this, and in the light of the supporting evidence, the writer believes that during the early development of the Bighorn "uplift" (i.e., during the preliminary stages of the Laramide revolution) the Tensleep fault was in existence and separated the southern and central segments of the Bighorn Range which were probably outlined at that time as gently and oppositely tilted crustal blocks.

During the early stages of uplift and tilting of these crustal blocks, and before they were strongly crowded together by compressive stresses, the Tensleep fault probably acted as a normal or tension fault. It has inherited features of this first stage of development such as the usual direction of drag being down on the upthrow (north) side and up on the downthrow (south) side. Also, the movement was down on the hanging wall, or south, side. Later, during the operation of maximum compressive stresses in the Laramide revolution, the southern and central segments of the Bighorn Mountains were crowded together and definite indications of their

[6] Max Demorest, personal communication.

compressive stage along the intervening (Tensleep) fault are superimposed upon the evidence of earlier normal faulting.

ACKNOWLEDGMENTS.—The writer wishes to acknowledge his indebtedness to W. T. Thom, Jr. and R. T. Chamberlin. To N. H. Darton the writer is indebted for the assistance rendered by his earlier report on the geology of the Bighorn Mountains. Likewise, the writer wishes to acknowledge the helpful co-operation of Max Demorest, who mapped the adjoining part of the eastern front of the Bighorn Mountains. G. P. Woollard, Lyman Toulmin, M. Q. Peterson, William Heroy, Jr., and Franz Dykstra efficiently assisted in the mapping. The entire party offers its thanks to Mr. and Mrs. William Hatfield and to Mr. Wight for hospitable camping facilities.

RECENT GLACIAL STUDIES OF THE NUGSSUAK REGION, WEST GREENLAND

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This paper is a review of two publications which deal with some of the results of the University of Michigan–Pan American Airways Greenland Expedition of 1932 and 1933.[1] This expedition, which had both a geological and a meteorological[2] program to carry out, selected for its base camp the Nugssuak Peninsula south of Melville Bay in Lat. 74°19′. The same region was studied thirty-six years earlier by the Cornell Greenland Expedition of 1896 lead by Professor R. S. Tarr. The writer—one of the five Cornellians who accompanied Tarr—is pleased to see the results of this later work on a region of exceptional interest to glacial geologists getting into print. In the region where the Cornell party spent a month in midsummer, the University of Michigan Expedition remained a year. The work of Professor Tarr in west Greenland in the nineties represented largely pioneer reconnaissance studies. It achieved important results in establishing the significant fact that the belt of practically ice-free mountains of the Nugssuak Peninsula and the Duck Islands had once been covered by the inland icecap which had a thickness of at least 3,000 and probably 4,000 feet[3] near the present western margin of the icecap, and extended at least 30 miles seaward of the present western limit. This conclusion is fully supported by the work of the Michigan geologists.

The scantiness of the drift west of the inland ice and the ruggedness of the topography as it appears from the sea had led Professor

[1] R. L. Belknap, "The Michigan–Pan American Airways Greenland Expedition Preliminary Results," *Geog. Rev.*, 1934, pp. 205–18; Max Demorest, "Glaciation of the Upper Nugssuak Peninsula, West Greenland," *Sonderabd. aus d. Zeitsch. f. Gletscherkunde*, Vol. XXV (1937), pp. 36–56.

[2] Belknap, "The Michigan Expedition to Northwest Greenland, 1932–33," *Polar Record*, 1935, pp. 32–35.

[3] R. S. Tarr, "Former Extension of Cornell Glacier near the Southern End of Melville Bay," *Bull. Geol. Soc. Amer.*, Vol. VIII (1896), map, pp. 251–68.

T. C. Chamberlin,[4] previous to Tarr's studies, to question any considerable former seaward extension of the Greenland icecap.

Dr. Belknap's paper gives the narrative of the expedition and a preliminary statement of some of its results. Dogs and light sledges, capable of 90 miles per day, were used in traveling. He tells us that one result of the westward movement of the great ice sheet across the mountain ridges of the Nugssuak Peninsula and through its bordering fiords during the period of the maximum extent of the icecap is seen in the "rather smooth appearance of the mountainous area when viewed from the east." Most of the land elements, however, end abruptly in steep slopes or cliffs on the seaward side[5]—a condition maintained by the sapping action of the ice foot and waves. The occurrence of partially eroded cirques leads Professor Belknap to believe that mountain glaciers were active before the icecap covered the entire coastal land strip.[6] For these, Demorest[7] postulates either a preglacial or an interglacial origin. The wide distribution of erratics is noted by both authors. A boulder belt paralleling the present ice front across the peninsula was recognized about a mile from it.[8]

The ice in the Cornell Glacier, Belknap states, was almost motionless during the winter season. Camp Watkins, the inland station on the icecap, was established at an elevation of 8,840 feet, about 75 miles west of the Continental Divide as established by Koch and Wegener in 1913. In going inland, a series of terraces or ridges—steep on the west side but flat or with a slight back slope on the east side—were encountered for more than 25 miles. From a point 55 miles inland the ridges become imperceptible and the slope unrecognizable without the use of the level. The rise in the last 25 miles was less than 250 feet.[9] In a marginal zone of the inland ice more than 40 miles wide, Belknap found that ablation is greatly in excess of precipitation, the snow entirely disappearing in summer and part

[4] "Recent Glacial Studies in Greenland," *Bull. Geol. Soc. Amer.*, Vol. VI (1894), p. 219.

[5] "Michigan–Pan American Airways Greenland Expedition," *op. cit.*, p. 213.

[6] *Ibid.* [7] *Op. cit.*, p. 55.

[8] Belknap, "Michigan–Pan American Airways Greenland Expedition," *loc. cit.*

[9] *Ibid.*, p. 216.

of the underlying ice as well. Inland, however, these conditions are reversed and precipitation is far in excess of snow waste, 14 inches of snow having accumulated at Camp Watkins during the seven weeks that inland station was occupied during July and August.[10]

In the physiographic description of the Nugssuak Peninsula, Mr. Demorest describes the straight transverse U-shaped valleys which in the eastern half dissect the mountainous peninsula approximately at right angles to its general trend. Starting from high cols, they become deep U-shaped valleys cutting nearly to sea-level. These are present where the higher peaks rise above 3,000 feet. In the western part of the peninsula a different type of transverse valley is found rising from sea-level on both sides of the peninsula and meeting on flat median divides. Through-valleys of the latter type the writer has observed in the Lake Melville region in Labrador.

The structure of the Nugssuak Peninsula is reported by Demorest to be complex and "in no sense has it been worked out in detail. . . . . The pre-Cambrian bedrock of Nugssuak is gneiss," of which at least four different types occur.

The glacial history of North America is recorded in terminal moraines and till sheets of contrasted types. No comparable record of the history of the Greenland icecap has been preserved owing to the dissipation of glacial erosional products via icebergs. This has made the problems of multiple glaciation in Greenland very difficult. The small valley glaciers and névés of the Nugssuak Peninsula are confined to the north side where protection from the midday sun and the wind-drifted snow favor their development. The largest of these, Nugssuak Glacier, Demorest found to have retreated about 200 yards from its 1896 position. The valley glaciers and névés he finds to represent not remnants of the former extension of the icecap over the peninsula but the return of colder climates. Evidence of this is found in the presence of a few névés without englacial debris, and with ice in the lower layers which disintegrates in a different way from ice which has been subjected to great pressure. Some unoccupied cirques in the peninsula have been scored and polished by the ice of the continental ice sheet, thus dating them before at least one great expanding period of the Greenland icecap.

[10] *Ibid.*

Mr. Demorest concludes that a continental glacier ceases to carry a large load at an early period in its history as a result of removal during the advancing stage of the part prepared by rock decay for easy transportation. The essential characteristics of the two contrasted regions of the icecap east of Cornell Glacier he has clearly outlined in Table 1.[11]

TABLE 1

Thin Ice Border	Interior Regions
Zone of greatest ice wastage	Zone of greatest ice accumulation
Zone of ice relief reflecting the underlying topography	Zone of practically no ice relief
Zone of ice movement primarily by direct gravity flow through the underlying valleys	Zone of ice movement by hydrostatic pressure
Zone where erosion increases the relief of the underlying land	Zone where erosion tends to decrease the relief of the underlying land except along longitudinal valleys
Zone of tensional stresses in the ice especially at the surface; therefore abundant crevasses	Zone of compressional stresses in the ice; therefore few crevasses

In discussing glacial erosion, Demorest stresses the old age phase in the cycle, when after removal of all the weathered and fragmental material only solid rock remains, which instead of being further eroded may be protected by glacial ice without eroding tools. It is only the old age deposits that are preserved to any considerable extent in the Nugssuak Peninsula. The paucity of morainal deposits on the Nugssuak Peninsula ceased to be a puzzling phenomenon when it was recognized that the Greenland icecap once extended to or beyond the western end of the peninsula and the Duck Islands. During the maximum extension of the icecap, ice-transported material must have nearly all reached the sea as it does now by way of glaciers and become widely distributed by icebergs.

All the geologists who have discussed the ice-borne sediments of

[11] *Op. cit.*, p. 50.

the Cornell Glacier have been impressed by their limited volume of visible transported debris. Of the land moraines Tarr wrote: "To me it was extremely disappointing to find nothing that closely resembled the great moraines of the United States."[12] Describing the appearance of the front of the Cornell Glacier, he says: "This ice wall was of marble whiteness throughout its entire extent—no sign of debris on the ice surface—none revealed in the 200 or 300 feet of a point which rises above the sea nor was there either lamination or stratification."[13] He, however, pointed out that this deceptive evidence is corrected by observing calving icebergs with loads of debris in the basal beds displayed as they turn over. All the median moraine extending seaward from Mount Sherman, a nunatack 9 or 10 miles east of the glacier front, disappears through the agency of streams and crevasses before the glacier front is reached. The speedy disappearance of the nunatack-rock debris picked up at Mount Sherman means that it probably reaches the bottom of the glacier and supplies it with the tools for fiord-deepening in the middle of the valley which it occupies immediately east of the sea front. While only two nunatacks are now present in the basin of exudation of this glacier, Demorest states that the sites of future nunatacks are indicated by "badly crevassed ridges and domes." These as they are uncovered and exposed to atmospheric weathering will, the writer believes, supply considerably more rock debris to the glacier than they do now and will correspondingly stimulate erosion in the valleys concerned.

It is only along the margin of the ice border where it meets the ice-free eastern base of the Nugssuak Peninsula that the material carried by the lower layers of the ice can be closely examined. None of the papers dealing with this area has described this marginal ice zone and its significant although small morainal deposits as fully as its importance seems to warrant. Concerning this zone Demorest writes:

> Where the inland ice ends on land, without outlet through low valleys to the sea, practically no deposits are being formed although fine material is found in-

[12] R. S. Tarr, "The Margin of the Cornell Glacier," *Amer. Geol.*, Vol. XX (1897), p. 148.

[13] *Ibid.*, p. 144.

terstratified in the lower layers of the ice. This appears to be due to the fact that in such places the ice is inactive. Movement is confined to outlets through the valleys.[14]

Along this marginal zone (August 20, 1896) the writer examined the ice border and moraine adjacent over a distance about 4 miles from the southwest corner of the north arm of Cornell Glacier. Since the recent sea shells then found on the morainal deposits and in the ice appear not to have been seen by other observers either there or elsewhere in Greenland, field notes referring to them are abstracted from the writer's notebook as follows:

About 2½ miles back from the glacier front the ice forms two lakes. The lower one has vertical walls of ice on the east 60 or 75 feet high which calve bergs. The upper lake was drained; the vertical ice wall on the east of it was 60 feet high. This ice is stratified, the lower 10 feet containing an abundance of boulders, gravel, also fragments of shells less abundantly but quite common; they are numerous in the morainal material here which is 390 feet (aneroid) above sea level. About 1½ miles north of above, the margin of the ice is bordered by little or no moraine for ¼ mile or more but has small morainal masses on its sloping surface 50 to 100 feet from the margin of two classes—(a) small cones 3 feet high and 3 to 10 feet across of fine loess-like material, and (b) masses of boulders, gravel and mud 50 feet across. A few shell fragments occur in these deposits which are 585 feet (aneroid) above the sea.

Moraine at S.W. corner (N. arm) Cornell glacier. The moraine here is composed of well-rounded boulders, mostly of gneiss and grey boulder clay; throughout the mass there is an abundance of living bivalve shells well broken up, entire specimens being rare. At the end of moraine the summit is about 15 feet above sea level; farther back it is 20 feet. A small pond 40 or 50 feet long rests on it.

Six species were identified[15] from the shells found in the moraine and the ice. Dredging by the writer in the fiord opposite the Cornell Glacier indicated *Saxicava rugosa* to be the most abundant shell. A few pectens and echinoderms, also numerous worms and crustaceans, were associated with the saxicavas living on a soft clay-mud bottom. New ice on the fiord near Cornell Glacier began to be troublesome on August 19, 1896, half an inch being recorded in the writer's notes as present on that date in places in front of the Cornell Glacier. One other record of marine shells in recent marginal ice deposits has

[14] *Op. cit.*

[15] E. M. Kindle, "Pleistocene Fossils from Baffinland and Greenland," *Science*, Vol. VI (1897), p. 92.

come to the writer's notice. P. Schei found recent marine shells in the morainal material of Leffert Glacier, Ellesmere Island (Holtedahl).[16] These and the shells found by Kindle along the land margin of the Cornell Glacier are the only records of this kind known to the writer. It seems probable, however, that when careful search is made others will be found elsewhere in the icecap marginal moraines which border the ice-free land areas in northwest Greenland. Such deposits appear to indicate for the glaciers represented a relatively recent retreat followed by an advance.

One might expect to find good examples of potholes in the Nugssuak Peninsula region where an extensive land area once deeply covered by ice is now for the most part concealed neither by ice nor by till. But as far as published reports indicate they have not been observed by either the Cornell or the University of Michigan Greenland parties. In Labrador they have been discovered in such an unpromising location as the summit of an isolated 1,400-foot mountain.[17] Mr. Demorest believes that the universal cover of glacial boulders in the transverse valley bottoms may conceal them.[18]

Another feature of the Labrador landscape which is missing from the Nugssuak shoreline is the boulder reef. Examples of these curving lines of boulders near the level of low tide are common about the head of Hamilton Inlet.[19] E. P. Wheeler II[20] has observed them in the Nain district. They develop along the sea margin of the intertidal zone near an abrupt transition from shoal to deeper water under the influence of tidal action and boulder-bearing ice.

[16] Olaf Holtedahl, "Summary of Geological Results," *Rept. 2d Norwegian Arctic Expedition in the Fram, 1898–1902*, No. 36 (1917), p. 25.

[17] E. P. Wheeler II, "The Main Noak Section of Labrador," *Geog. Rev.*, Vol. XXV (1935), Fig. 9, p. 245.

[18] Personal communication.

[19] Kindle, "Geology and Geography of Lake Melville District," *Can. Geol. Surv. Mem. 141*, Pl. 14, p. 63.

[20] *Op. cit.*, Fig. 8.

THE COMPOSITION OF METEORITES

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ABSTRACT

Convincing evidence has been found that the generally accepted ideas regarding the average composition of meteorites are incorrect, owing to the fact that collections have not been completely representative.

If the accepted "composition of meteorites" is incorrect, then all reasoning with regard to their terrestrial relations is subject to error. The survey which the writer has been conducting since 1923 has brought to light facts which strongly suggest such an error.

It has been customary to take the analyses of all recorded meteorites and to calculate from them an average composition. This composition is then used for purposes of comparison with terrestrial rocks and for the interpretation and solution of other problems relating to meteoritic matter. Obviously, it is of utmost importance that the data from which this average composition is deduced shall be completely representative of all the different varieties of meteorites which reach the earth, and that these varieties be used in their proper proportions, each in the same ratio as in the actual showering of matter from space to the earth.

The first discrepancy which appeared between the older records and those which we made as a result of a planned search was in the ratio between stony and metallic meteorites. The proportion of stony meteorite falls represented in our list of finds is 80 per cent as against 32 per cent in the total list of all finds in North America previous to the beginning of our survey. Considered from the standpoint of weight, we find that of 215 North American siderites and aerolites whose weights were recorded by Farrington in 1909, 98.4 per cent were metallic and 1.6 per cent stony. Comparing the yield of these two classes in our own survey, we find that the ratio is 14 per cent metallic and 86 per cent stony. Our ratio is much more in harmony with that which had been noted among witnessed falls. Several writers had already commented on the inconsistency be-

tween the ratios of stone to iron in witnessed falls and in finds of unwitnessed falls. This inconsistency was so striking that it led to several attempts to explain it. Dr. George P. Merrill once went so far as to suggest that possibly there had been a change in the nature of the meteorite increment subsequent to the infall of the older finds. Our educational program on the recognition of meteorites, however, has clearly demonstrated that the discrepancy was due only to the fact that stony meteorites had generally escaped recognition except in cases where they were seen to fall.

This demonstrated fact at once suggests that perhaps there are still other types of meteorites arriving on the earth which not only laymen but scientists fail to recognize. It is also logical to suspect that those rarer groups of meteorites such as amphoterites, chladnites, howardites, eucrites, angrites, and the carbonaceous forms are rare for the simple reason that they have not been recognized and recovered. Strangely enough, of the nine witnessed falls that have been recovered in the southwest since the beginning of our survey, four have been of these so-called rare groups. Equally impressive is the fact that the other five, which belonged to the common chondritic groups, were found by laymen in the usual manner and reported without the aid of a scientific survey. The Johnstown chladnite fell in the presence of some two hundred persons, and consequently was also recovered and reported without the aid of any survey. The other three—namely, Sioux County, Nebraska, Pasamonte, New Mexico, and Crescent, Oklahoma—would almost certainly never have been discovered had it not been for the persistent activities of scientists who set out definitely to find them by means of surveys.

Fourteen years of experience in field problems connected with meteorites leads to the suspicion that meteorites of the types which have been considered rare may constitute a considerable percentage of the cosmic rain of matter. It is likewise conceivable that the earth receives meteorites of types which are entirely unknown to us. Some of these perhaps arrive as solid masses while others fully as massive as the largest-known meteorites are entirely reduced to dust, and, though their voluminous clouds are sometimes visible for a considerable time, the material is unidentified when it reaches the

soil. The Pasamonte and Sioux County falls are both very friable and are of such a composition that, even though a thousand tons of such crushed material had been scattered over the territory which lay beneath the cloud which each produced, it would never have been discovered. Only a few pounds of each of these two falls are known to have arrived in chunks large enough to attract attention.

The writer has long been aware that the educational program which our laboratory conducts in rural communities and which has resulted in so many discoveries is far from adequate to meet this problem. In order to be effective we must emphasize only the characteristics of those meteorites which present the simplest problems of identification. To describe all the types would merely lead to confusion and the whole effort would fail.

With the shifting of the mean farther toward the stony end of the scale we are doubtless nearer to a correct understanding of the composition of meteorites than formerly; but certainly we are not yet in a position to make any final deductions. If all geologists were familiar with the seventy or eighty varieties of meteorites which are now known, and if all their students were made to realize the importance of reporting suspected specimens, advances in this field could be made more rapidly than in the past and soon we should be able to evaluate better the part played by these bodies in geological processes and in the development of the earth.

DISCUSSION: THE DISINTEGRATION AND EXFOLIATION OF GRANITE IN EGYPT

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In his interesting description of the disintegration and exfoliation of granite monuments in Egypt, Donald Barton[1] has clearly demonstrated that the exfoliation has developed in historic time and only on surfaces exposed to moisture. He concludes (p. 111) that "this exfoliation in Egypt cannot be even partly hypogene" and that "much of the extensive known disintegration and exfoliation of granite in the moist temperate regions of the world is not a result of unloading of the rock but an effect of moisture, presumably hydration plus incipient further alteration."

If speed of development of exfoliation is important, the rapid exfoliation in Egypt may be matched by an instance of even more rapid exfoliation after unloading, called to my attention by W. Armstrong Price,[2] who described the expansion and exfoliation of cores of Tertiary sandstone and shale which developed when they were brought to the surface from oil wells drilled in Texas. He first noted the structure in cores taken from 2,500 feet below the surface. The large-scale exfoliation of glaciated surfaces of the Sierra Nevada granite has been ascribed to dilation after unloading,[3] and it has developed nearly as rapidly and much more abundantly than the exfoliation in Egypt.

Rock exfoliation has developed in widely diverse geologic environments, and many processes[4] appear to have been involved. Among them, hydration seems to have been prominent, but possibly each

[1] "Discussion: The Disintegration and Exfoliation of Granite in Egypt," *Jour. Geol.*, Vol. XLVI (1938), pp. 109–11.

[2] Personal letter, October 4, 1937.

[3] François E. Matthes, "Exfoliation of Massive Granite in the Sierra Nevada of California" (Abstract), *36th Ann. Meeting Geol. Soc. Amer.* (1936).

[4] Eliot Blackwelder, "Exfoliation as a Phase of Rock Weathering," *Jour. Geol.*, Vol. XXXIII (1925), p. 793.

has been dominant in certain localities. Dilation, after unloading of rock masses, has been the principal process in some cases,[5] and in others it may have been secondary—the action having been held in check until the attack of weathering had weakened the cohesion of the rock sufficiently to permit dilation.

The granitic rocks, in which most exfoliation is found, are not native to the surface of the earth and are seen only after they have been unloaded by erosion of overlying rocks. Metamorphic rocks and most volcanic and sedimentary rocks are also under subnormal load at the surface, and a tendency to dilate must be inherent in them even if it is not often active.

Where granite monuments in Egypt were attacked by weathering, hydration may have been the immediate cause of the exfoliation, but load had been removed from the granite, and it is entirely possible that the inherent dilatational forces were released by the weathering and became an auxiliary factor. The Egyptian occurrences do not invalidate my generalization that dilation after unloading is the only one of the suggested processes which is always available at localities where rock exfoliation is found.

[5] Rollin Farmin, "Hypogene Exfoliation in Rock Masses," *Jour. Geol.*, Vol. XLV (1937), pp. 626 ff.

REVIEWS

The Geology and Biology of the San Carlos Mountains, Tamaulipas, Mexico. By L. B. KELLUM, E. H. WATSON, E. S. BASTIN, R. W. IMLAY, L. R. DICE, A. M. CHICKERING, R. V. CHAMBERLIN, C. L. HUBBS, and H. T. GAIGE. "University of Michigan Studies: Scientific Series," Vol. XII. Ann Arbor: University of Michigan Press, 1937. Pp. xi+341, pls. 30, maps 13 (2 in color). $5.00.

The San Carlos Mountains are an east-west trending range about 40 miles long and 25 miles wide that rises sharply to a height of 3,500 feet or more above the coastal plain of northeastern Mexico, some 50 miles west of the gulf coast, 100 miles southwest of Brownsville, Texas, and nearly 200 miles northwest of Tampico. Much as the Black Hills are an outflung portion of the Rocky Mountains, the San Carlos range is an outpost of the great Sierra Madre, lying to the west. Geologic studies of the San Carlos area should be of special interest because Cretaceous sedimentary rocks, distant from any others, are here lifted to the surface, because the structure of the range may be expected to give clue to the type of folding and trend of structural features in the bordering lowland, where possibility of oil and gas production exists, and because of several types of igneous rocks and of metalliferous ore deposits in the district. These chief aspects of geologic investigation in the San Carlos Mountains first came to the notice of Lewis B. Kellum when he made a reconnaissance survey of the area for an oil company in 1925. In 1930 an expedition of the University of Michigan was organized under Dr. Kellum's direction for the purpose of more detailed geologic and biologic studies of the San Carlos Mountains. Field parties included, besides Kellum, E. S. Bastin, R. W. Imlay, G. W. Rust, and E. H. Watson, geologists, H. H. Bartlett, botanist, and L. R. Dice, zoölogist. These workers appear to have conducted their investigations separately for the most part, during various lengths of time that are vaguely stated or not given, and the described methods of study as well as the results seem to vary widely, from carefully detailed investigation of some features to extremely hasty reconnaissance of others. The fruits of the labors, including not only field work done under conditions that must have brought many discomforts but also much laboratory and office work, are satisfying. This is perhaps especially true because of the unusually fine quality of the publication

that has been issued. Whatever deficiencies the report may have, it seems proper to charge these chiefly to limitations in opportunity for investigation, and the authors, especially Dr. Kellum, may feel a just pride in the published work.

The sedimentary rock column of the San Carlos district includes somewhat less than 1,000 feet of Lower Cretaceous strata, mostly massive limestone, all of which is classed as Tamaulipas limestone, and, conformably above this, some 4,000 or 5,000 feet of Upper Cretaceous beds, and, with indefinite lower boundary, approximately 1,000 feet of Eocene deposits. The Lower Cretaceous rocks are believed to be mainly of Fredericksburg age, a transition zone at the top of the Tamaulipas formation being regarded as equivalent to Washita deposits of the Texas area. The Upper Cretaceous beds are divided into the San Felipe formation, consisting of thin-bedded limestone and shale, about 900 feet thick, and, above this, the Mendez shale, about 2,850 feet thick; then follows undifferentiated shale, 1,800 feet thick, classed as Upper Cretaceous or Eocene. The San Felipe beds are correlated with the Woodbine, Eagle Ford, and Austin formations of Texas, and the Mendez shale with the Taylor and part of the Navarro formations. The stratigraphic presentation, which is divided between a general discussion by Kellum and a description of the northeastern district (Sierra de Cruillas) by Imlay, is very ill arranged, obscure, and even confusing. For example, study of all of this portion of the text and accompanying charts leaves doubt as to presence or absence of Jurassic beds and as to whether Kellum and Imlay think one way or the other about it, or are in doubt. Lack of clearly stated introductory generalizations or summaries and an infelicitous mingling of major and minor elements of all sorts make quest of significant features difficult.

Contributions to the paleontology of the San Carlos Cretaceous beds are contained in the respective chapters by Kellum and Imlay, the former treating of eighteen forms, none specifically identified, and the latter describing two species.

Structural geology of the San Carlos Mountains is well depicted in at least its salient features by several maps and sections, and there are accompanying descriptions in the text, chiefly by Kellum and Imlay. Additional information of interest appears in the chapters on igneous rocks by Watson, and ore deposits by Bastin. The dominant structures are east-west trending folds of rather gentle type, the axial portions of various anticlines being broken in places by igneous intrusions; there are no important faults.

Igneous rocks of the district are mainly intrusives, masses of laccolithic nature being the most prominent. Associated with these are dikes and sills. Extrusive rocks are unimportant. Good descriptions of the petrology of these igneous rocks are given in a chapter by Watson, and for part of the northeastern mountains by Imlay. Gabbro, diorite porphyry, calc-alkalic and alkalic phanerites, and a variety of dike rocks are types that are described petrographically.

Economic geology of the San Carlos region is concerned essentially with deposits of copper, lead, and silver. Numerous old mines and prospects are located in the area but there is very little present activity in mining. A concise, well-organized chapter describing the general characteristics of the ore deposits, discussing their origin, and giving details by districts and individual mines is contributed by Bastin. The copper deposits occur in diorite or diorite porphyry at or near contacts with limestone, rather than in the limestones; the primary ore mineral is chalcopyrite. The lead-silver deposits occur chiefly as fissure veins and subordinately as replacements of limestone; silver-bearing galena is the chief ore mineral.

Chapters describing mammals, spiders, fishes, amphibians, and reptiles observed in the San Carlos Mountains region comprise sixty-two pages in the latter part of the volume.

The beautiful full-tone plates which are distributed through the San Carlos report add much to the fine appearance of the book. Excellent press work and binding are also to be noted.

RAYMOND C. MOORE

"The Geology of Texas," Vol. III, Part I: "Upper Paleozoic Ammonites in Texas," by F. B. PLUMMER and GAYLE SCOTT; Part II: "Permian Fusulinidae of Texas," by CARL O. DUNBAR and JOHN W. SKINNER, in *University of Texas Bulletin 3701*. Austin, 1937. Pp. 825, pls. 81, figs. 93.

Paleozoic stratigraphers and paleontologists everywhere will doubtless come to regard this volume as one of the most outstanding state survey contributions of noneconomic type. Director Sellards and the Texas Bureau of Economic Geology, as well as the four authors, merit the thanks of the entire geological profession for significant contributions creditably printed and excellently illustrated.

In Part I, Plummer and Scott describe the Texas Carboniferous ammonoids, which are classified as belonging to 7 clans, 28 families, 70

genera, and 139 species. Of these, 10 families, 12 genera, and 58 species are new. Altogether, 516 pages, 71 figures, and 41 plates have been efficiently employed in this section of the publication.

The authors evaluate the previous work on Texas ammonoids and give valuable chapters on classification and methods of description. They also outline the ammonoid zones in various parts of Texas. The north-central area of the state affords the most complete section with 16 ammonoid zones, 2 in the Upper Mississippian, 8 in the Pennsylvanian, and 6 in the Permian. The ammonoids, however, do not yield very important information regarding the boundary between the Pennsylvanian and Permian systems. Furthermore, a glance at the chart showing stratigraphic occurrence (Fig. 88) will show that at least some of the species have a relatively long geologic range. But the authors attempt to bolster our time-honored faith in ammonoids as almost perfect index fossils by stating that species in one zone "can generally be distinguished from species in a zone a few feet above or below." Yet all but two of the recognized zones are separated by much more than "a few feet," and the *Artinsia adkinsi* zone of the Wolfcamp and the following *Perrinitis compressus* zone of the Hess are separated by more than 2,000 feet of strata barren of ammonoids. The authors also point out that "unfortunately most of the best index fossils are the rarest forms, and these are absent in many outcrops." (It is perhaps fair to suggest the possibility that these species may not be such good indices if and when they are found in greater abundance.)

Plummer and Scott state further that since some of the species recapitulate characters, and others were more slowly evolving, the changing features of the septa cannot be relied upon completely for correlative purposes. Hence they have correlated their zones by means of "assemblages," each of which is made up of from three to fifteen species.

Following Spath's excellent suggestion (1934) that a marine epoch might well be designated by the name of its most widespread genus, Plummer and Scott have given cephalopodan epoch names to the divisions of the late Paleozoic in Europe and America. On the basis of this scheme the Kungurian of Europe and the Upper Permian of America would be known simply as *Waagenoceran*, the Upper Artinskian of Europe and the Middle Permian of America as *Medlicottian*, etc.

The section on classification is a particularly valuable paleontologic contribution, although it is a little remarkable that the words "ammonoid" and "ammonite" should be used so interchangeably, and that the former was not employed in the title. The authors demonstrate that *Prouddenites* is not a direct ancestor of *Uddenites*, and that *Proshumardites*

is not ancestral to the American *Shumardites*. Having clarified this situation, they then proceed to make things a little difficult for future paleontologists by erecting a new genus, *Preshumardites*, whose name is certain to cause some confusion. But of course these are minor complaints against an altogether admirable piece of work.

In Part II, Dunbar and Skinner give an equally exhaustive treatment of the Permian fusulinids. The microstructures of these fossils have been studied in thin section with such great care that it has been possible for the authors to give a check list of 38 valid genera (out of about 50 proposed) and 540 species. Some vague idea of the progress of micropaleontology in little more than the past half-century may be gleaned by comparing this multiplicity of recognizable forms with the single genus, *Fusulina*, which embraced all known fusulinids when Zittel's *Handbuch* first appeared in 1876.

The systematic description of the Texas forms includes 11 genera and 57 species, of which 3 genera and 45 species are considered new. Two hundred and ten fossil localities are listed, and an approximately complete bibliography of 176 works is included. The stratigraphic summary, with the faunal zones established, and the sections on methods of study and morphology of shell wall will be much appreciated by serious workers both in micropaleontology and in subsurface stratigraphy. The 40 excellent plates in Part II, like the 41 in Part I, are of the finest grade of heliotype engraving. In marked contrast, however, are text Figures 92 and 96, which leave much to be desired.

As is fitting for such significant papers, the Texas Bureau has issued this publication well bound and attractively printed on a fine-grade, light-weight paper which has kept the volume from being bulky despite its more than eight hundred pages.

CAREY CRONEIS

Silicate Analysis. By A. W. GROVES. London: Thomas Murby & Co., 1937. Pp. xxi+230; figs. 11. 12*s*. 6*d*. net.

As pointed out by Professor Holmes in his Foreword to the volume by Dr. Groves, our knowledge of the distribution of the elements is still rudimentary despite the thousands of analyses of minerals and rocks that have been made. This paucity of data is in part due to the practice of

limiting the number of constituents determined to twelve or fifteen. It is in respect to this point that the volume seems of special value to the reviewer, namely, in the determination of the less common constituents.

In addition, the standard procedures for the more common rock and mineral components are given in detail, as well as special procedures for some components under special conditions and for analyses where the material is scanty. Of note is the section on methods to be used in the analysis of materials of commercial and technical value such as coal ash, ceramic materials, mineral dust, etc.

The book is designed both for chemists and for geologists. The latter will find the chapters on the laboratory and its equipment, the reagents, sampling and crushing, and "common operations" of particular value. Much of this material will be familiar to a good analytical chemist. The geologist with some training in analytical chemistry should be able to use the book as a guide to analytical work. The chemist will welcome the chapters on the geochemical aspects of the problem as well as the chapters on errors and on computations as a check on the accuracy of chemical analyses.

The book is well set up. The procedures are printed in boldface type. Detail is good. Precautions to be taken are emphasized and reasons for the various steps are carefully stated so that the work may be intelligently pursued.

The book, even if not used as a laboratory guide, will be found of some use to the petrologist and mineralogist who deal with analyses. The chapter devoted to the methods of assessing the value of chemical analyses is of special value. The chapter on the occurrence of the various elements will interest most geologists as it contains a good summary of our present knowledge of this problem.

As the author, himself a petrologist, points out, the petrological paper consisting solely of petrographical descriptions and illustrations of thin sections is becoming a thing of the past. Chemical analyses of the principal rock types and of some of the constituent minerals are essential to both petrological and mineralogical research. The mineralogist should be as well equipped to record the chemical composition of a mineral as to determine its crystallographic and optical characteristics. These attributes are mutually dependent, and an omission of any one renders a study incomplete. Dr. Groves is to be thanked for the preparation of a volume which will assist in the attainment of high standards of silicate analysis.

F. J. PETTIJOHN

Thron der Goetter: Erlebnisse der ersten Schweizerischen Himalaya Expedition. By ARNOLD HEIM and AUGUST GANSSER. Zuerich and Leipzig: Morgarten Verlag Aktiengesellschaft, 1938.

This semipopular account of the first Swiss Himalaya Expedition deserves the attention of geologists for several good reasons. First of all, because it is the record of the human side of a geologic expedition. There is great need of books that tell of the adventurous side of geologic exploration. Like most engineers, geologists take strange environments and unaccustomed situations that call for resourcefulness and special skills merely as personal matters, inevitable incidents in a job to be done. Unless those who have the gift record how they lived, traveled, and worked while they opened up new fields of geologic knowledge, the precious human side of this phase in the history of science will be lost forever. Much is lost already.

Heim and Gansser's work was, of course, not written as a record of geological exploration. It is a contribution to semipopular geographical literature and as such can be counted with the best. But there are choice sidelights on geological work under peculiar difficulties. All is told with that understatement and humor which grow out of the life in the field.

Second, because it is illustrated with 220 photogravure reproductions of exquisite photographs and two large, folded plates of panoramas. Those who doubt the adequacy of the modern small camera for the purposes of publication should study the pictures in this book. One of the authors used a Leica camera; the other, larger standard equipment.

Third, because the book is accompanied by a map of the central Himalayas, on which the relief is shown by contour lines (with 2,000 foot interval) and by shading in natural illumination from the southwest. While the scale of the map is too small for physiographic studies (1:650,000), it is full of interest in many ways.

Finally, the brief summary of geological results gives a glimpse of the scientific work achieved. In a few pages the major zones of structure which can be discerned in the cross section of the central Himalayas are described. Most remarkable is, perhaps, the observation that in the unfossiliferous and more or less metamorphic rocks of the zone, 100 kilometers wide, which lies southwest of the high central chains, metamorphism increases systematically from the bottom of the deep valleys to the tops of the mountains. There seems no escape from the conclusion that this belt represents recumbent anticlinal structure of stupendous dimensions. During a recent visit the reviewer has seen some of the materials and especially the magnificent cross-section panoramas, which will

be presented in the scientific report of the expedition. When that report has appeared we shall be in the, for geologists, unusual situation of possessing, on the one hand, the scientific results, and, on the other, the human record of a strenuous field season of six months spent in the mightiest mountains of the earth by two extraordinarily gifted observers.

WALTER H. BUCHER

Ground Water. By C. F. TOLMAN. New York: McGraw-Hill Book Co., 1937. Pp. xvii+593; figs. 189. $6.00.

In this comprehensive volume on ground water the author has collected and integrated a vast amount of material. The subject is introduced with a brief historical review, and in the next several chapters are presented a résumé of the elements of ground-water hydrology and a discussion of the roles played by rainfall, runoff, evaporation, and transpiration. The subject develops in logical order, with a consideration of the nature of openings and pores in rock, the occurrence of water and the forces at work in the zone of aeration, and influent seepage and the nature of ground-water flow, with a discussion of rock permeability. These subjects are presented with an excellent balance between theoretical aspects and practical applications.

Discussion of the water table, ground water in fractures and solution openings, confined water, and a classification of artesian aquifers carries the subject through additional details. Wells, their types, factors affecting the quantity of flow, cone of water-table depression, and the like attest to the detail with which the book is organized. A similar chapter on springs is itself a treatise on the subject. A chapter is included on oil-field fluids, including a discussion of hydraulic conditions during the accumulation of the oil, and, later, under production. Final chapters on the ground-water inventory and ground-water provinces complete the volume.

In his Preface the author explicitly breaks with tradition by defining ground-water hydrology as an independent science, which draws upon geology and engineering for its data, but which also receives contributions from all the natural sciences. Certainly the manner of presentation is unlike that of a geology text, inasmuch as Dr. Tolman has no hesitancy in introducing quantitative concepts expressed in the language of mathematics. The writer of this review is wholly in sympathy with this increasing analytical tendency in problems of earth science.

Whether the subject of ground water remains as a branch of geology or establishes itself as a sister science, it goes without saying that this volume deserves the careful consideration of all geologists interested in ground-water phenomena. In conjunction with Muskat's *Flow of Homogeneous Fluids through Porous Media*[1] Tolman's book rightly marks an important advance in our understanding of ground-water problems.

W. C. KRUMBEIN

The Flow of Homogeneous Fluids through Porous Media. By M. MUSKAT. New York: McGraw-Hill Book Co., 1937. Pp. xix+763; figs. 284. $8.00.

Dr. Muskat's volume is presented as an analytical study of the flow of fluids through porous media, and as such is probably to be classified as a volume on physics. However, as an application of quantitative methods to the flow of water and oil through rocks the book is a significant contribution to geological science. The mathematical treatment is not simple, as such things are considered by geologists; neither is it unduly complex, considered as mathematical physics. Fortunately, the author summarizes each chapter in essentially non-mathematical terms, so that the implications of the reasoning are placed at the disposal of non-mathematical readers.

As the author points out (p. 8), there are many variables involved in natural situations, but, by assuming an ideal case, it is possible to elucidate the underlying principles in an analytical manner. Geologists as a group have been hesitant about simplifying natural phenomena, but Muskat's 750 pages of analysis are evidence that an analytical attack yields amply justified results.

The author presents his material in four parts. The first, comprising about 100 pages, introduces the necessary definitions, and such concepts as porosity, permeability, occurrences of ground water and oil-field fluids, as well as a discussion of Darcy's law, in terms both of its theoretical basis and of its application to permeability studies. The second part of the volume devotes some 450 pages to the steady-state flow of liquids. The subject is divided into two- and three-dimensional problems, and the use of potential-theory methods of attacking them. Gravity flow systems, questions of non-uniform permeability, and complexities due to two-fluid systems are comprehensively treated. The last chapter in this section discusses multiple well systems, in which the analytical methods are applied to problems of recovery from oil sands. The last two sections of the book

[1] Reviewed in *Jour. Geol.*, Vol. XLVI (1938), pp. 902–3.

are concerned respectively with the nonsteady-state flow of liquids and the flow of gases through porous media.

The petroleum geologist and the ground-water hydrologist will find the volume indispensable; the general geologist will find many examples of typical geological problems analytically discussed. As a companion volume to Tolman's *Ground Water*[1] Muskat's book will open new fields to the quantitative attack on ground-water problems, in addition to its significant contributions to the study of petroleum.

W. C. KRUMBEIN

The Geology of South-Western Ecuador. By GEORGE SHEPPARD. London: Thomas Murby & Co., 1937. Pp. 275; figs. 195. 25*s.* net.

This is the first book on the geology of Ecuador to be published in English. Although it covers only a relatively small area in westernmost Ecuador between the Gulf of Guayaquil and the Bay of Manta to the north, this strip may presumably be taken as typical of the portion of the country between the Andes and the Pacific, and this comprehensive treatment of its geology is therefore a welcome contribution. The chapter headings are as follows: (i) "Introduction"; (ii) "Climate and Physiography"; (iii) "Sedimentation of the Tertiary Formations"; (iv) "Stratigraphical Geology"; (v) "The Tertiary Larger Foraminifera of South-West Ecuador," by T. W. Vaughan; (vi) "Structural Geology"; (vii) "Cherts and Igneous Rocks"; and (viii) "Petroleum."

There have been recognized in Ecuador 15,000 feet of Tertiary sediments, which were brought down by streams from the uplifted Andes and deposited under various conditions. The Eocene series is the thickest and much of its material is thought by the author to have been laid down in an extensive estuary near the present site of the Gulf of Guayaquil, to which it was probably carried chiefly along ancient courses of the Guayas and Tumbez rivers.

An unconformity separates the Oligocene from the Eocene, resulting from a regional uplift which was accompanied by igneous intrusions. The strongest episode of diastrophism appears to have occurred at or near the close of the Oligocene, for the Eocene and Oligocene strata have been subjected to much more block faulting than the Miocene. Hypabyssal igneous activity accompanied or shortly followed this faulting. A general uplift of the Andean region, with more faulting, followed the Tertiary deposition but preceded the Quaternary.

As a result either of an omission of decimal points or of their failure to

[1] Reviewed in *Jour. Geol.*, Vol. XLVI (1938), pp. 901–2.

reproduce, the scale of miles in the sketch map (Fig. 19, p. 32) reads 10, 20, 30 miles instead of 1, 2, 3 miles. The error, however, is not serious as the same area is shown on three other maps with correct scales. An extensive Bibliography completes the volume.

R. T. C.

"Les Resources minérales de la France d'outre-mer," Part V: "Le Pétrole." *Publication du Bureau d'études géologiques et minières coloniales.* Paris, 1937. Pp. 263; figs. 37. Fr. 45.

This is the fifth of a series of publications on the mineral resources of the French colonial possessions and protectorates. It begins with a review of general principles governing the accumulation of petroleum and a brief explanation of prospecting methods. At the present time exploratory work is being pushed with vigor in Morocco, Tunis, Madagascar, and French Equatorial Africa. All operations are directed by the Compagnie française de pétroles, backed by the Office national des combustibles liquides. So far oil has been discovered at only one place, which is in Morocco, and the value of this discovery has not yet been fully ascertained. French West Africa, Indo-China, New Caledonia, the Antilles, and French Guiana seem to promise little in the way of petroleum possibilities. The main source of French supply continues to be Iraq, where the Compagnie française de pétroles controls approximately a one-fourth interest in the Iraq Petroleum Company. For this reason a full chapter is devoted to the Mesopotamian oil fields.

France, with all her extensive territorial holdings, has been consistently faced with the problem of meeting a domestic demand far in excess of domestic production. An interesting analysis of this situation, and of the steps which have been taken to meet it, concludes the bulletin.

WILLIAM F. READ

Mineral Tables. By ARTHUR S. EAKLE. Revised by ADOLF PABST. 3d ed. New York: John Wiley & Sons, 1938. Pp. 73. $1.50.

The approximately two hundred species covered by these tables are grouped into six divisions based on streak; four of these are further subdivided into two to six subdivisions depending on color. Arrangement within a subdivision is in order of hardness. The tables show no fundamental change from those of the second (1923) edition, except for the addition of four minerals. The booklet opens with a seven-page elementary description of those physical properties used in the tables.

D. J. F.